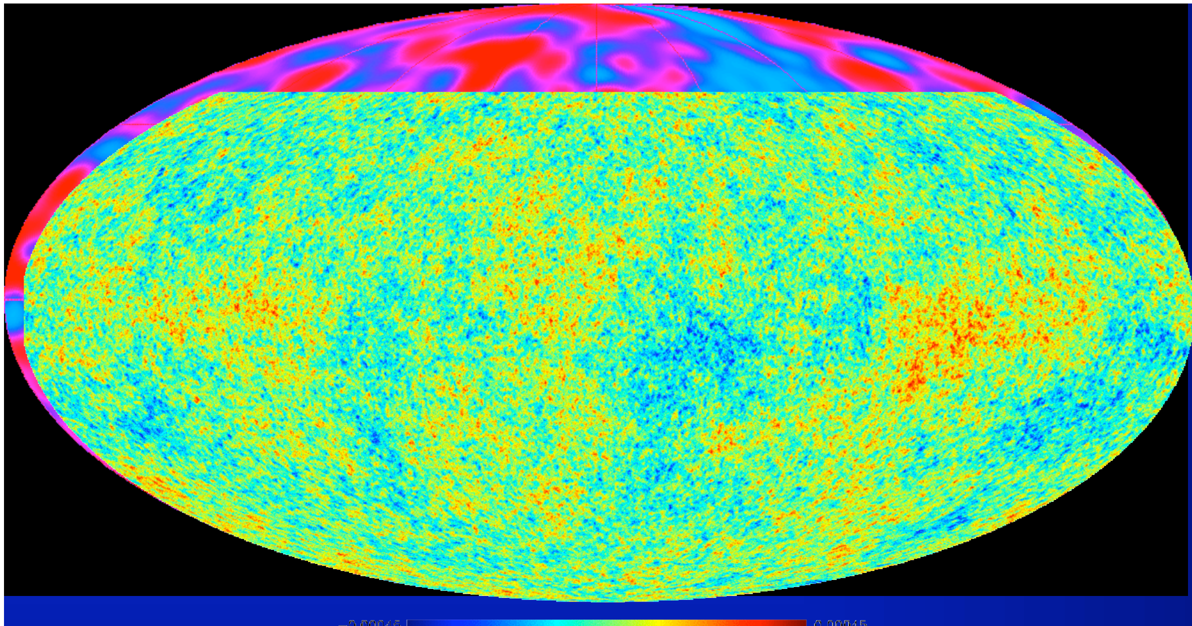
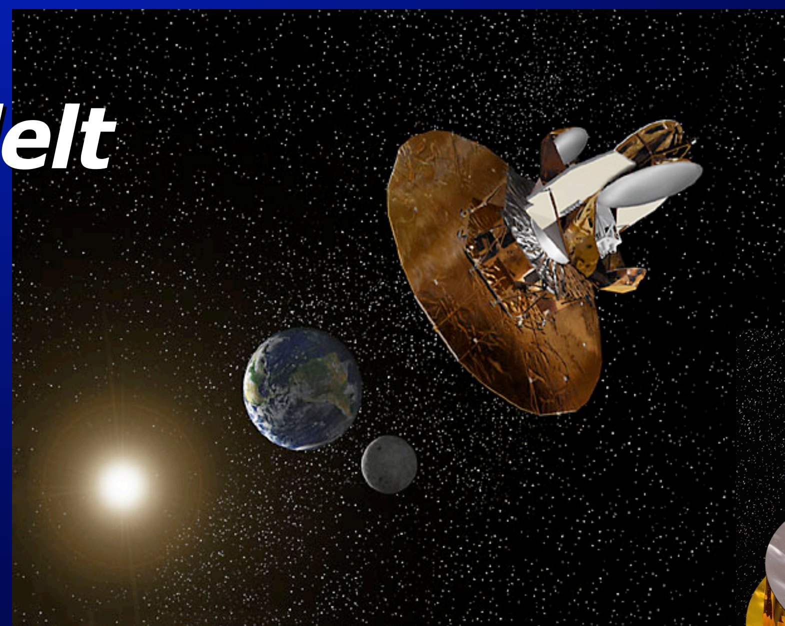
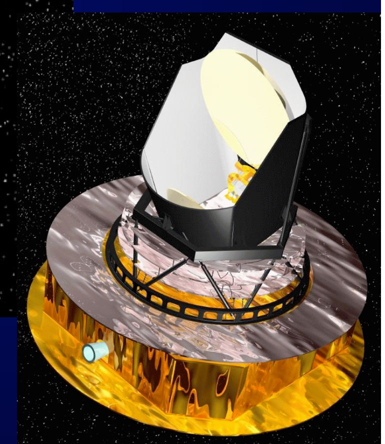


The Cosmic Microwave Background: Beyond Concordance





Benjamin D. Wandelt

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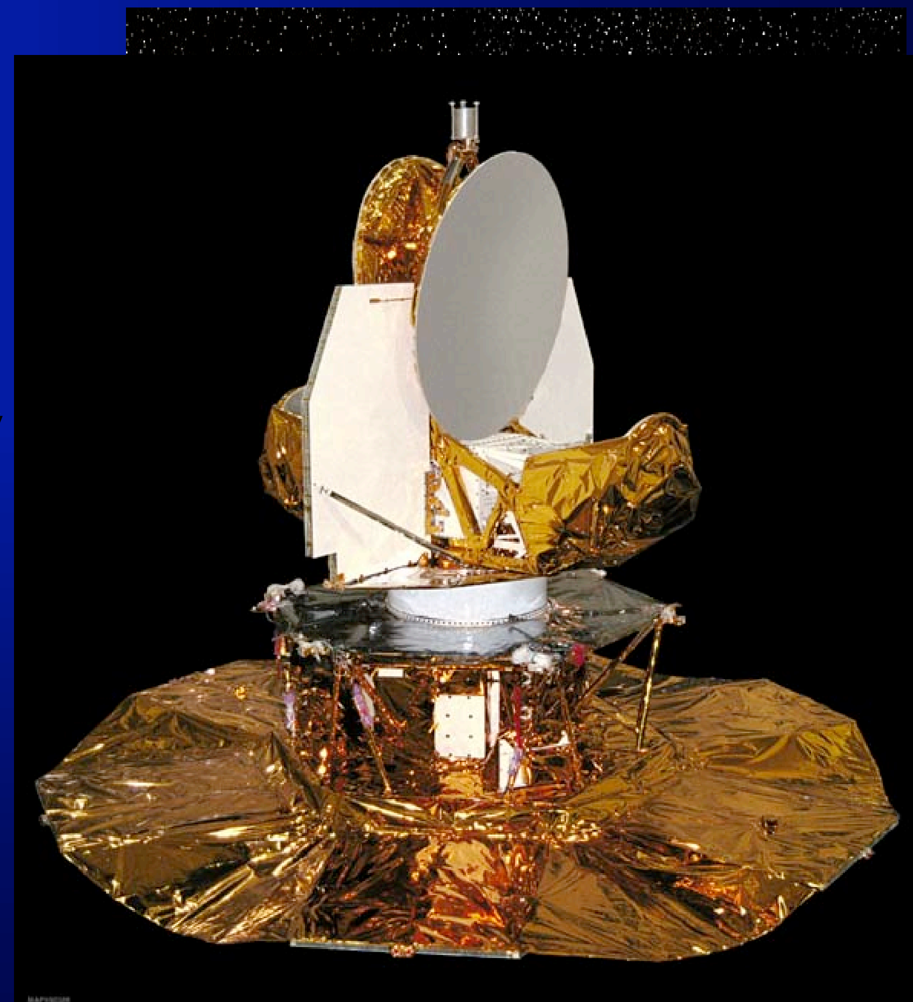
NCSA

Outline

- WMAP: Beyond Concordance?
- From Data to Cosmology - a Bayesian Approach
- Example: Analysis of the WMAP data
- Current and future directions

The Wilkinson Microwave Anisotropy Probe

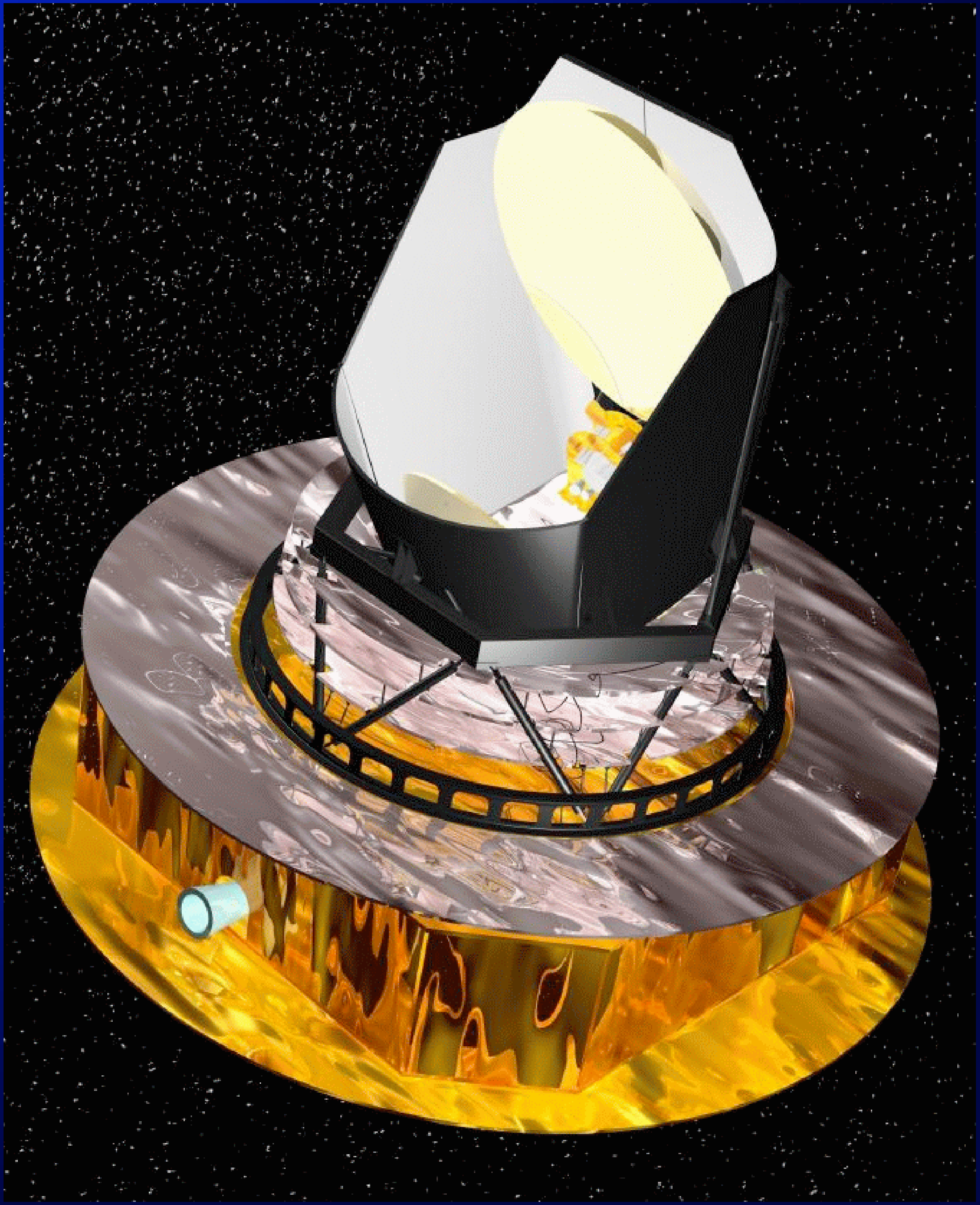
- NASA MIDEX mission
- Currently in Operation
  - Reached observing location (L2) in 2001
  - YR1 data released in early 2003
- Harbinger of precision cosmology
- *lambda.gsfc.nasa.gov*



Planck
HFI/LFI
(2007)

The definitive
CMB temperature
mission

Joint ESA/NASA
mission



So, what did WMAP do for us?

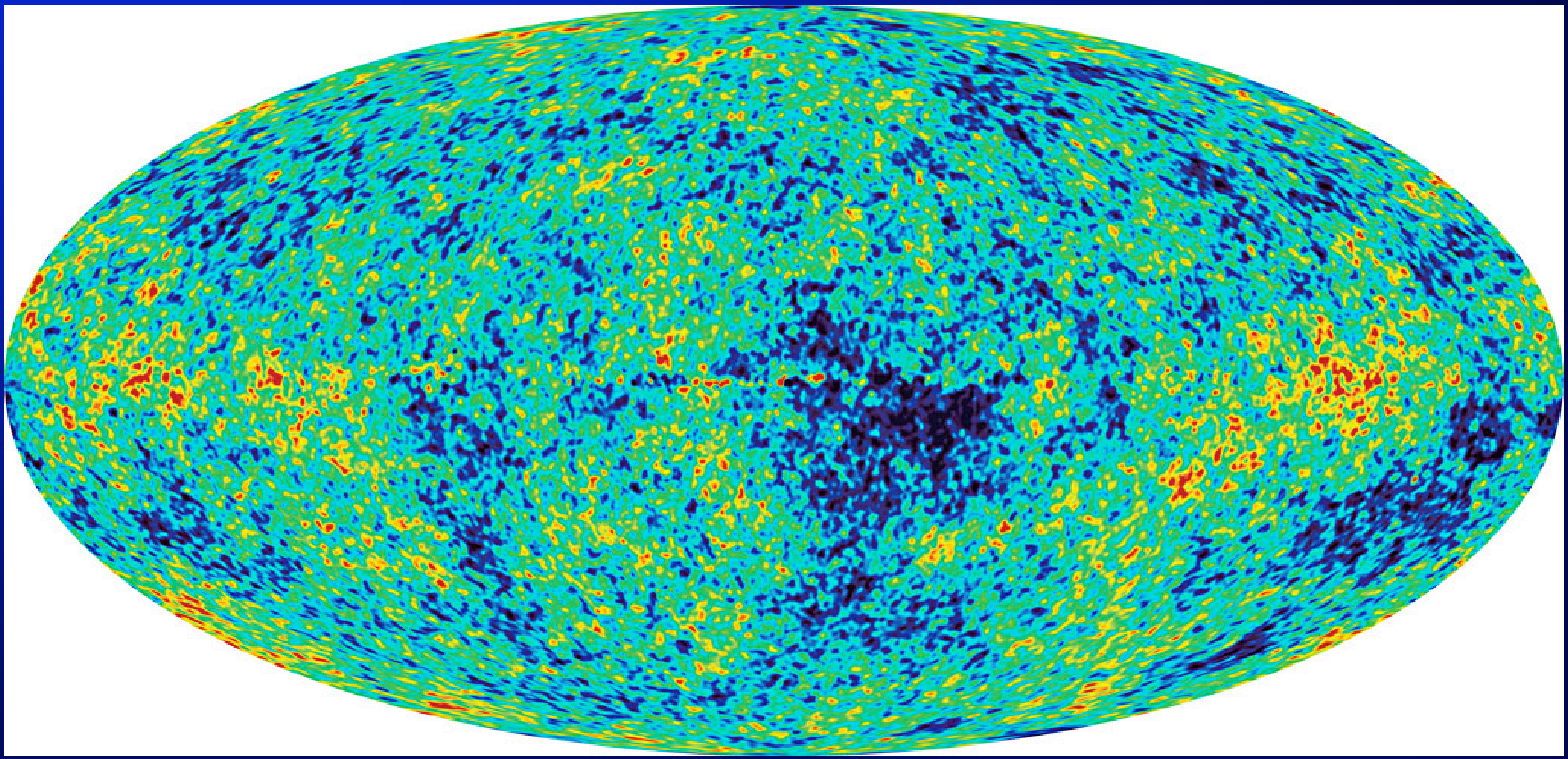
Maps

Power Spectrum

Cosmological Parameters

(More?)

WMAP "Internal Linear Combination" map of the CMB anisotropies

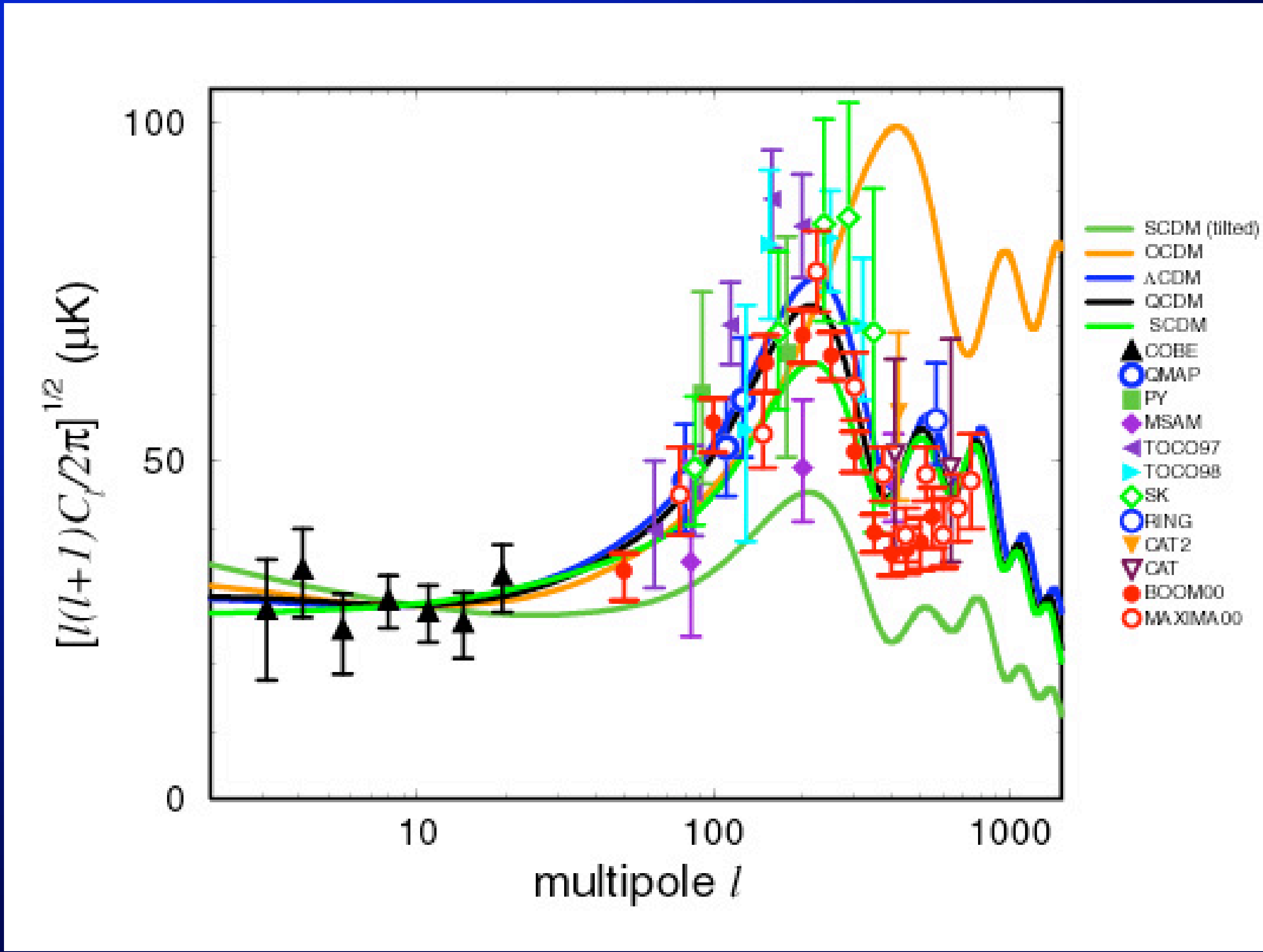


But this combined version is hard to use to do actual science…

Where is the information in the CMB?

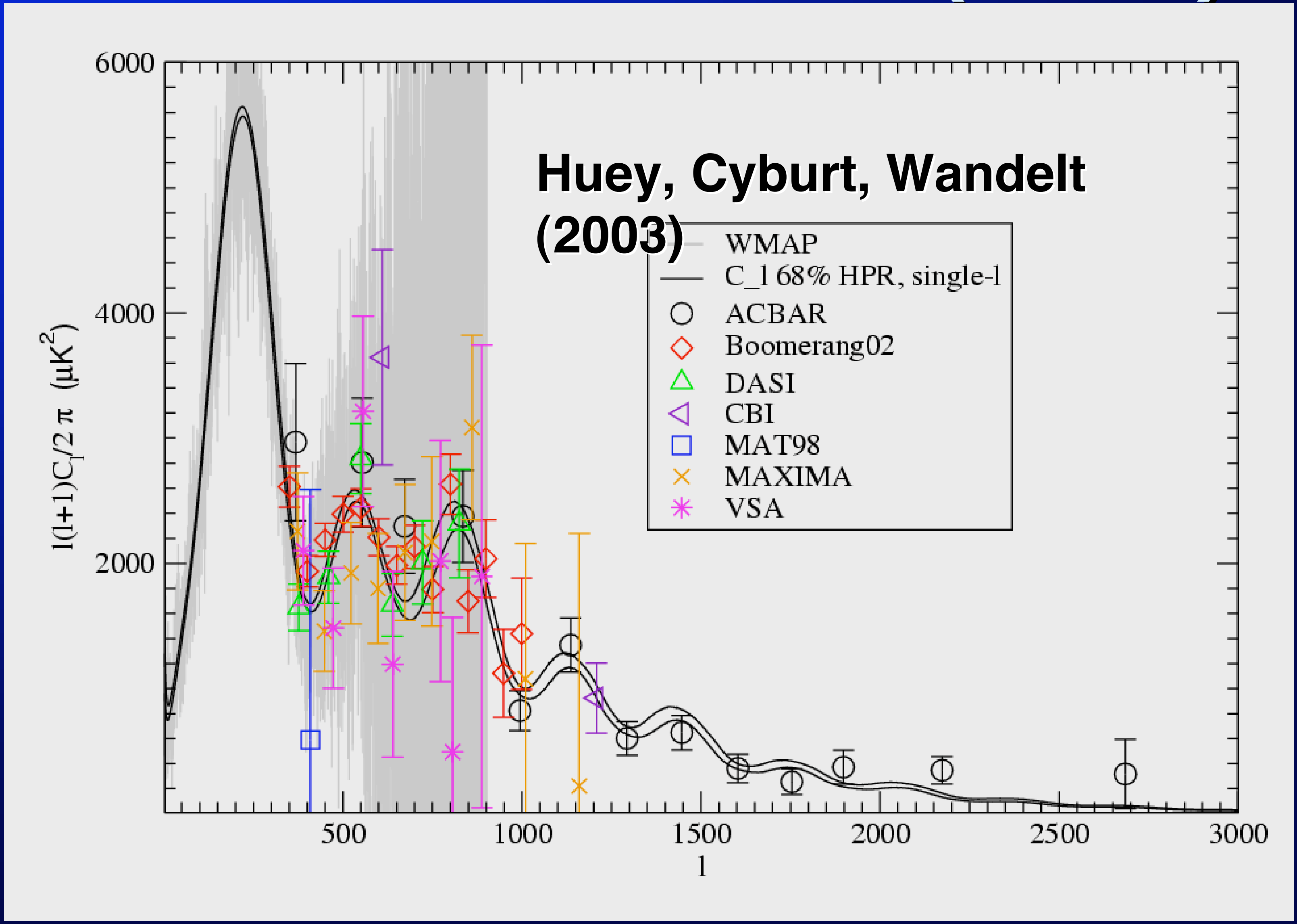
- In the standard cosmology it's not in the image - it's in the **correlations**
- These are quantified in terms of the **power spectrum C_l**, equivalent to 2-point function
- In principle, estimation is easy - essentially just compute spherical harmonic transform $a_{lm} = \int d^2n\, Y_{lm}(n)\, T(n)$.
- Then estimate $C_l = \left(\sum_m |a_{lm}|^2\right)/(2l+1)$.

Status 2002



Each Point = 1 PhD

Status Post-WMAP (2003)

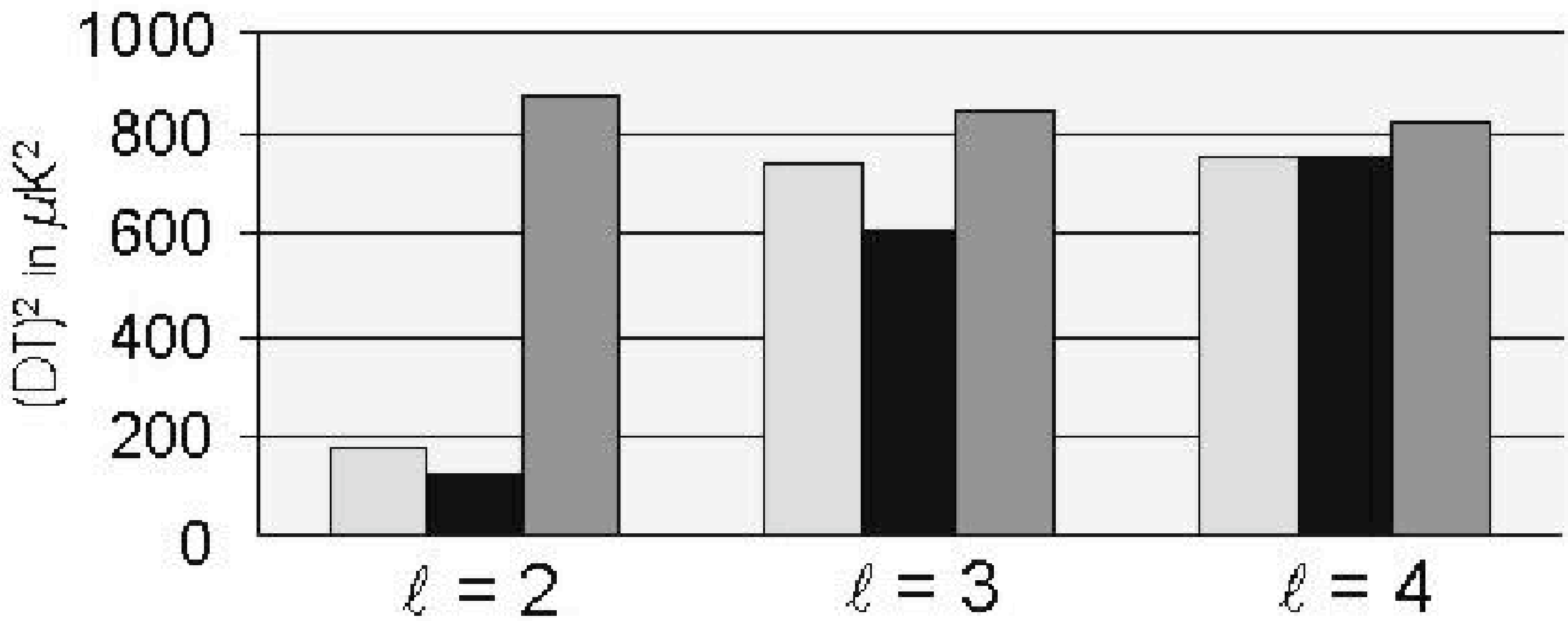


Were there any surprises?

New light (?) in the WMAP data

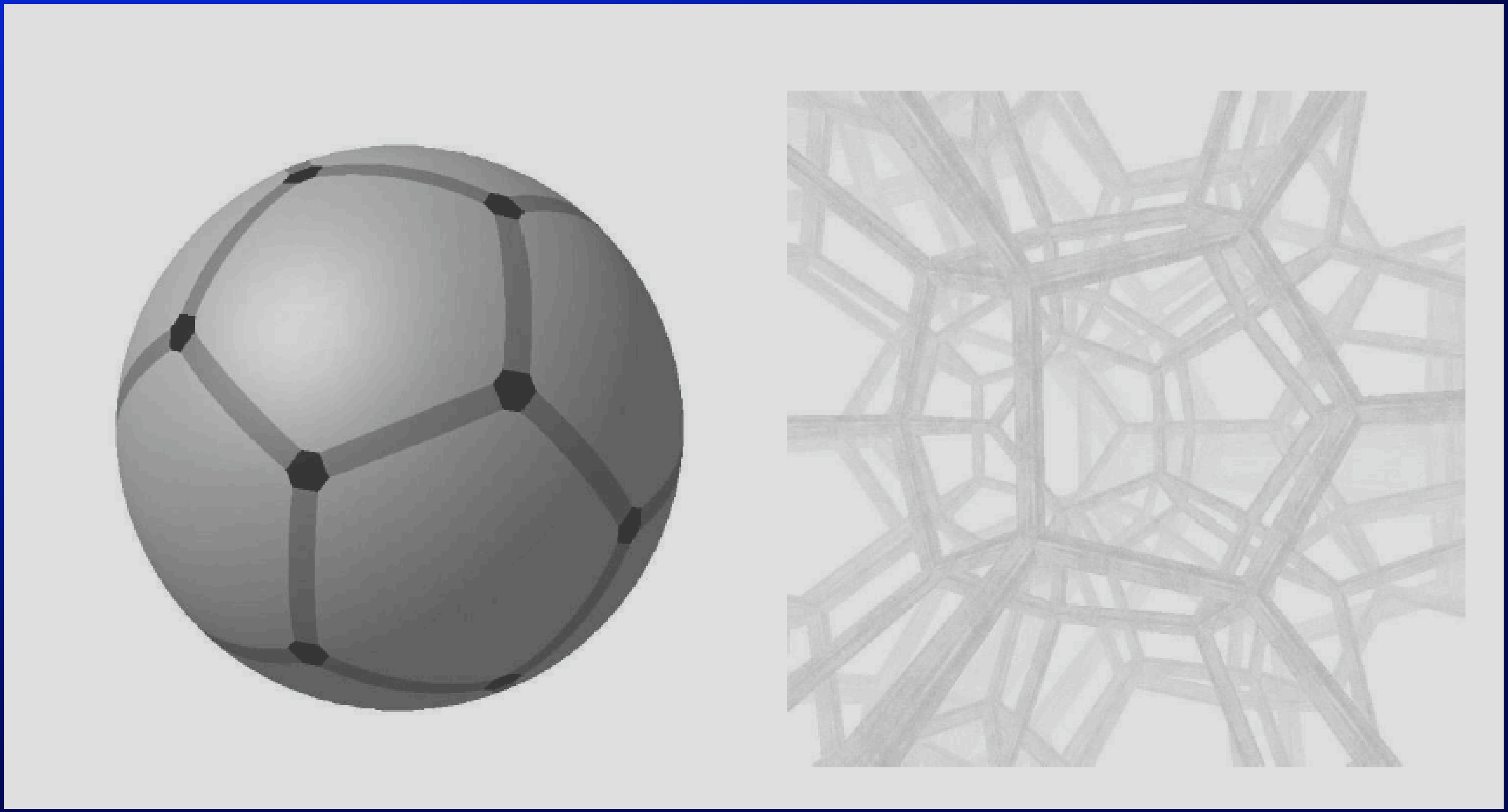
- Too little large scale power (WMAP team)?
- Earlier reionization than expected (WMAP team)
- Phase correlations (P. Coles et al)
- Anomalous moments of wavelet coefficients (L. Cayon et al)
- Preferred direction (Bianchi VII?) (H.-K. Eriksen et al)
- Hot and Cold Spots Anomalies (D. Larson & B. Wandelt)

Too little large scale power?



Luminet et al. 2003

So… a soccer ball Universe??



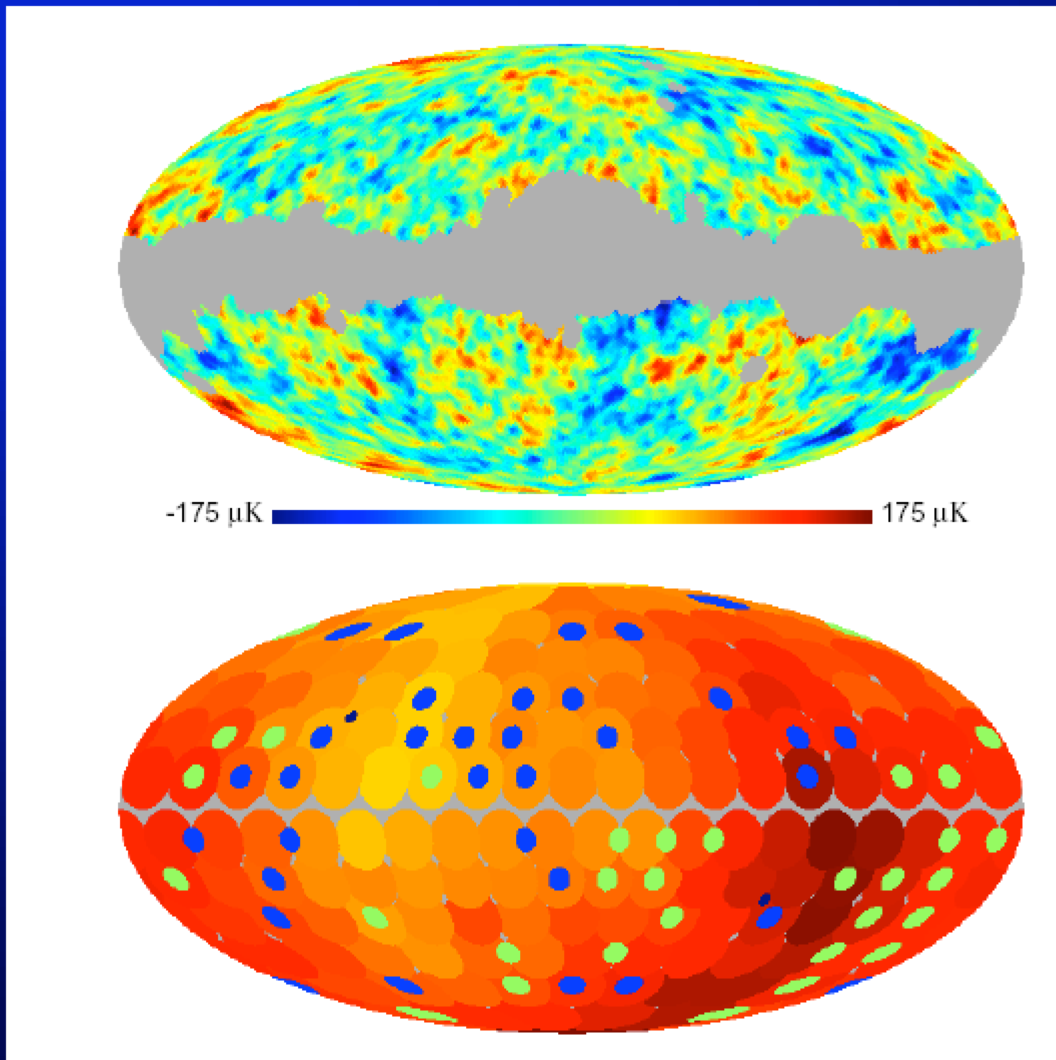
Luminet et al. 2003

Too little large scale power?

NOTE: NO ERROR BARS!

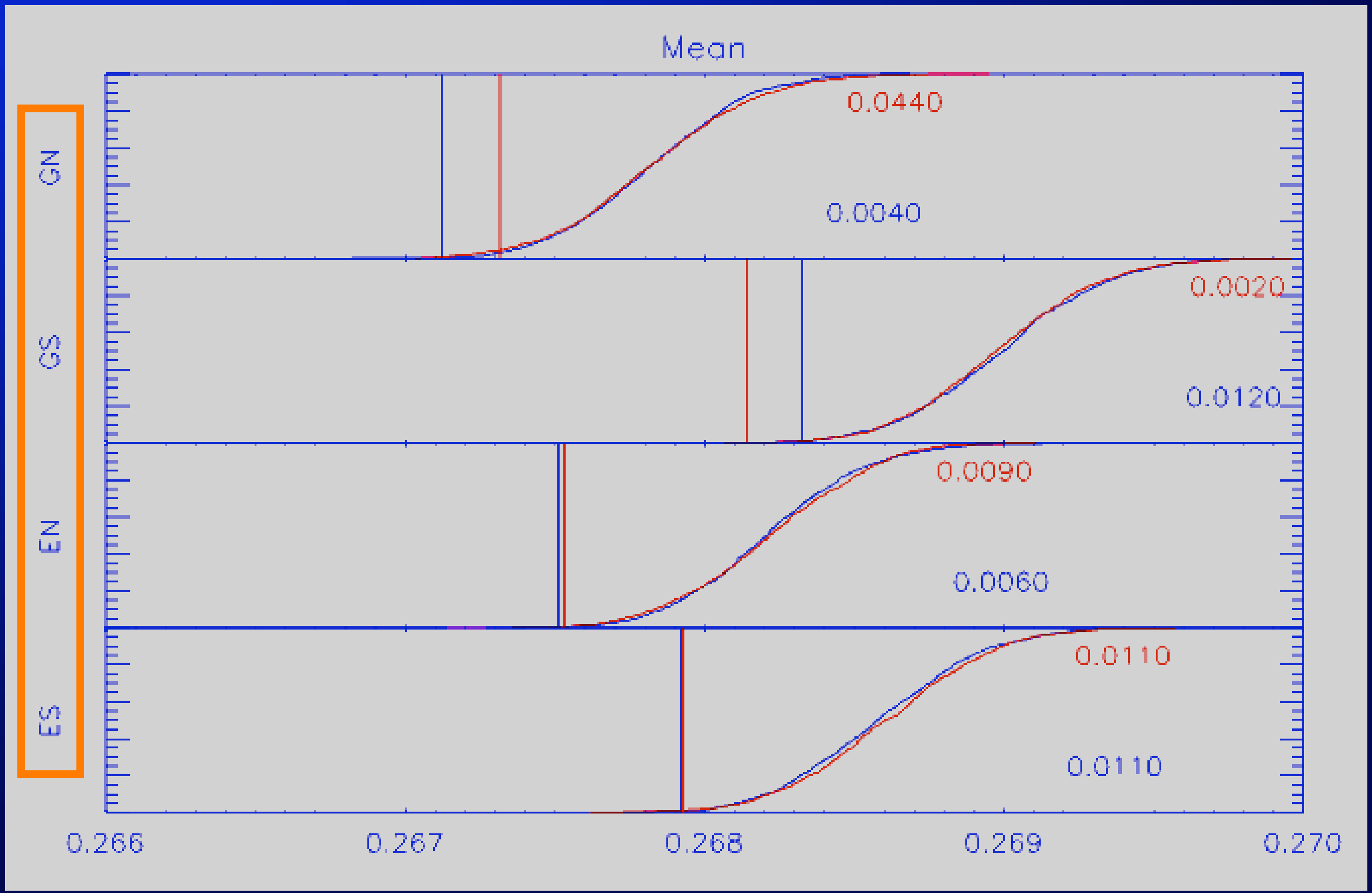
Luminet et al. 2003

A preferred direction?



Eriksen et al. 2003, 2005

The hot and cold spots aren't hot and cold enough



Larson and Wandelt, ApJL 613,85 2004

But hold on a second... how did we get all the way from the data to this point?

The Challenge of Interpreting CMB Data

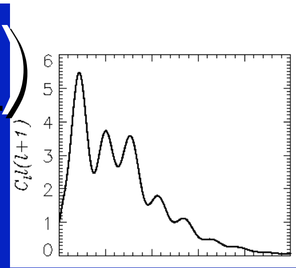
From Cosmology to Data -

from Data to Cosmology

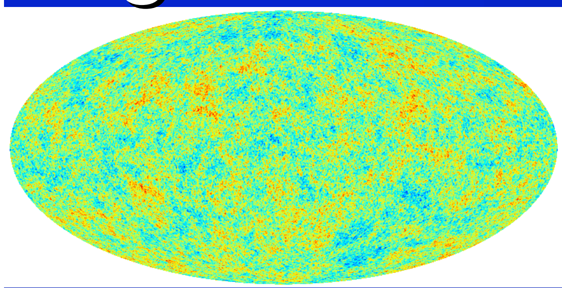
What are the data?

CPs:

$C_l(\_)$



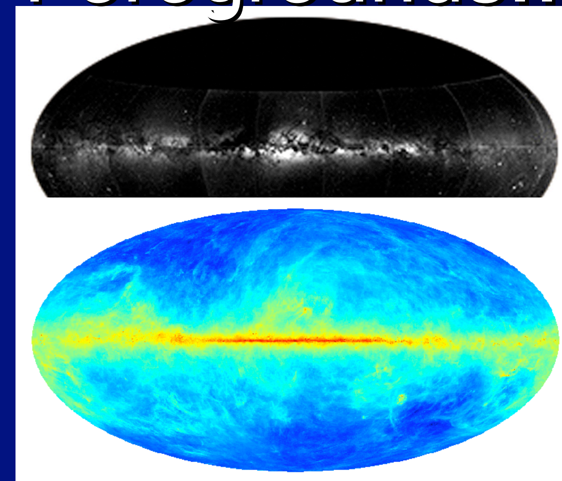
Signal



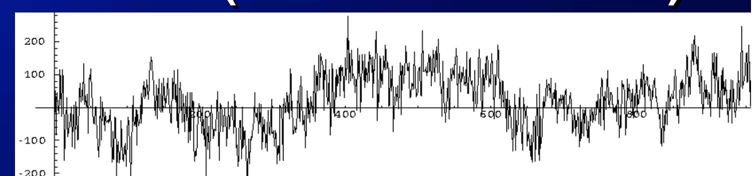
Sky

Frequency bands

Foregrounds...

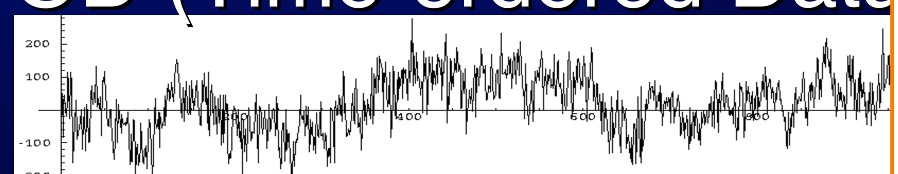


Noise (correlated?)



Optics, Scan Strategy, Internal Systematics, ...

TOD (Time-ordered Data



The Challenges

- Huge data sets (~10 TB for Planck data)
- Covariance estimation for $10^{6\text{-}8}$ numbers.
- Sample size=1
- Parameter estimation in 10-20 D.
- Hypothesis testing (Assumptions?)
- Using physical constraints/priors and non-CMB information
- Detailed quantification of uncertainty ("error bars") very important.

Power Spectrum Estimation

$$P(C_\ell|d) = \frac{\exp\left(-\frac{1}{2}\mathbf{d}^\mathbf{T}(\mathbf{S}+\mathbf{N})^{-1}\mathbf{d}\right)}{\sqrt{|2\pi(\mathbf{S}+\mathbf{N})|}}$$

- The signal covariance **S** is parameterised in terms of the **C_l.**
- This is a **non-Gaussian** density for **C_l**.
- Task: explore this likelihood (or posterior density)

- BUT: this involves determinant calculations.
- (S+N) is NOT sparse => **N^3** operations
- N~10^7, so 10^{21} ops for **a single likelihood evaluation**.
- At 10^{10} ops/s and π_10^7s/yr: **1000s of CPU years**.

_ Most current power spectrum analyses of large data sets use lossy estimators, that yield approximations to this likelihood, e.g. Pseudo-C_l (Wandelt, Hivon, Gorski 1998; Hivon *et al* 2001).

Can we beat the big **N^3**?

- **Definition of "power spectrum estimation:" mapping out/summarizing the density $P(C_l|d)$.**

- **$P(C_l|d)$ is a probability density for C_l. If computing it is impossible, an alternative way to map it out is to *draw random samples* from it.** **(Jewell et al. 2004, Wandelt et al. 2004)**
- **How do we do this?**

$P(C_l|d)$ can be represented as an integral over signal maps

- Write the joint posterior density for the C_l and the CMB signal map **and integrate numerically.**

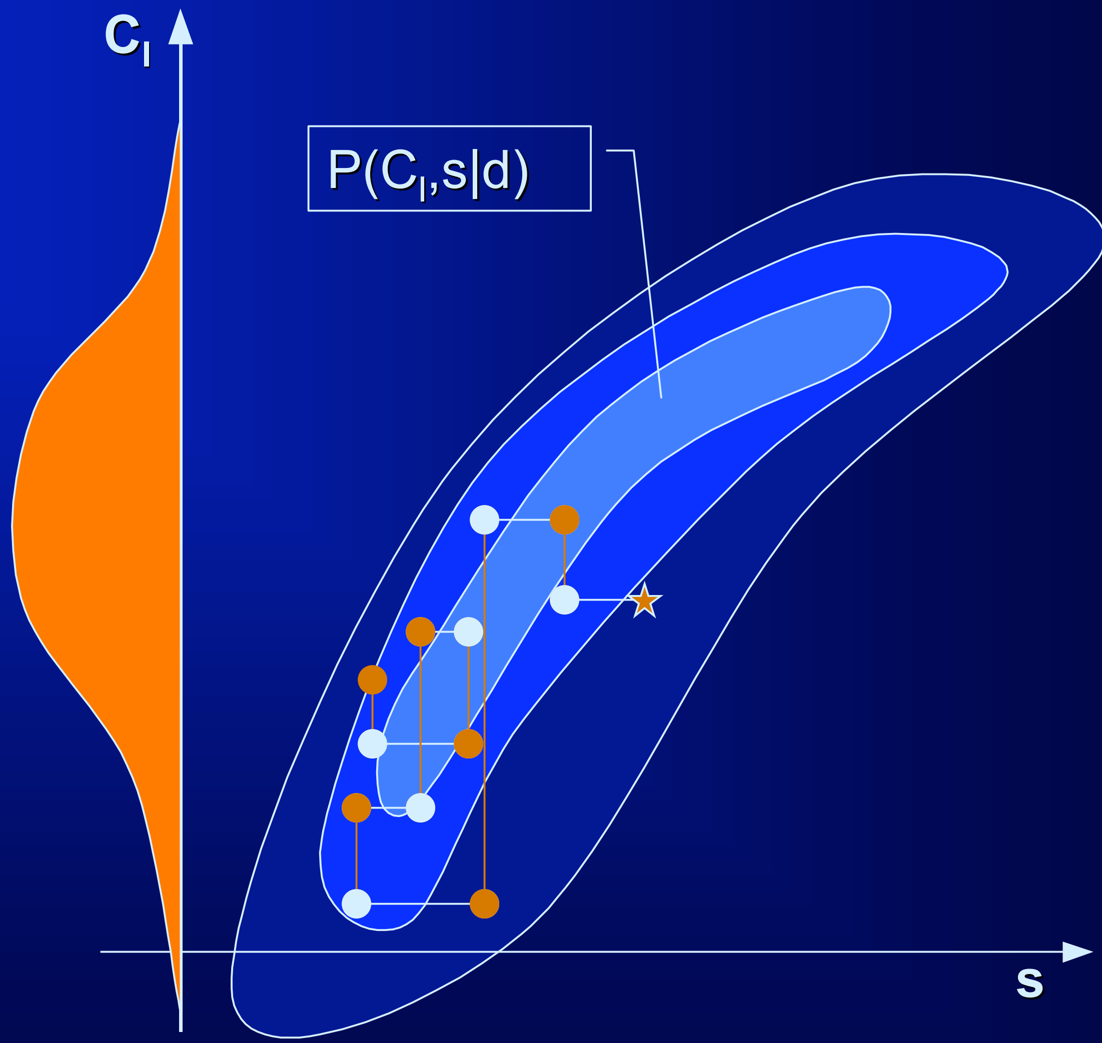
$$P(C_\ell|\mathbf{d}) = \int d\mathbf{s}\, P(C_\ell, \mathbf{s}|\mathbf{d}) \quad \text{(marginalization)}$$

$$P(C_\ell, \mathbf{s}|\mathbf{d}) \propto P(\mathbf{d}|\mathbf{s})P(\mathbf{s}|C_\ell) \quad \text{(Bayes theorem)}$$

$$P(C_\ell, \mathbf{s}|\mathbf{d}) \propto \frac{\exp\left(-\frac{1}{2}(\mathbf{d}-\mathbf{s})^{\mathbf{T}}\mathbf{N}^{-\mathbf{1}}(\mathbf{d}-\mathbf{s})\right)}{|2\pi\mathbf{N}|} \frac{\exp\left(-\frac{1}{2}\mathbf{s}^{\mathbf{T}}\mathbf{S}^{-\mathbf{1}}\mathbf{s}\right)}{|2\pi\mathbf{S}|}$$

Gibbs Sampling

- Gibbs Sampling is a way to construct a Markov Chain that moves at every step.
  - Divide the parameter space into orthogonal complements.
  - Random sample from the parameters in each complement, keeping the other parameters fixed.
  - Iterate.
- This leads to a sample from the joint density of all parameters.



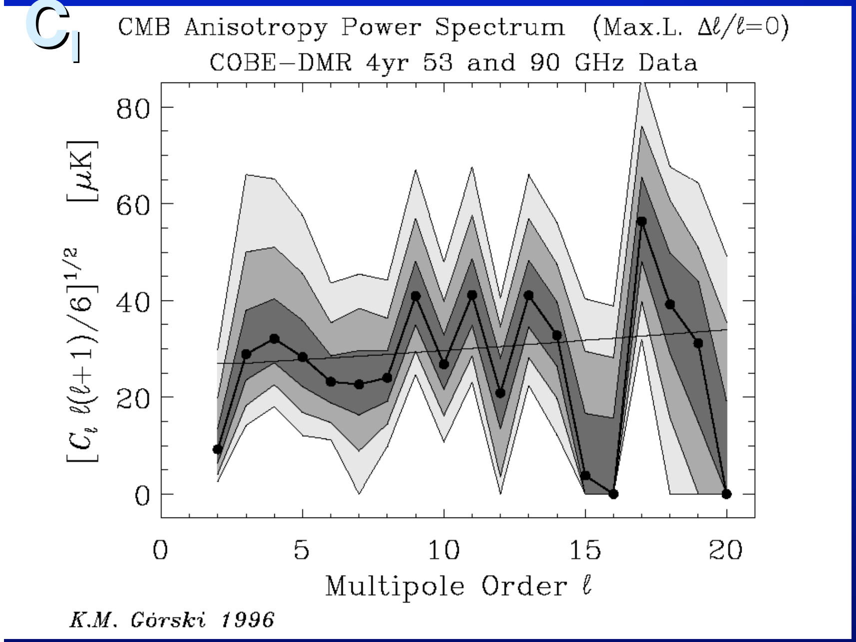
Example

Bayesian COBE-DMR analysis

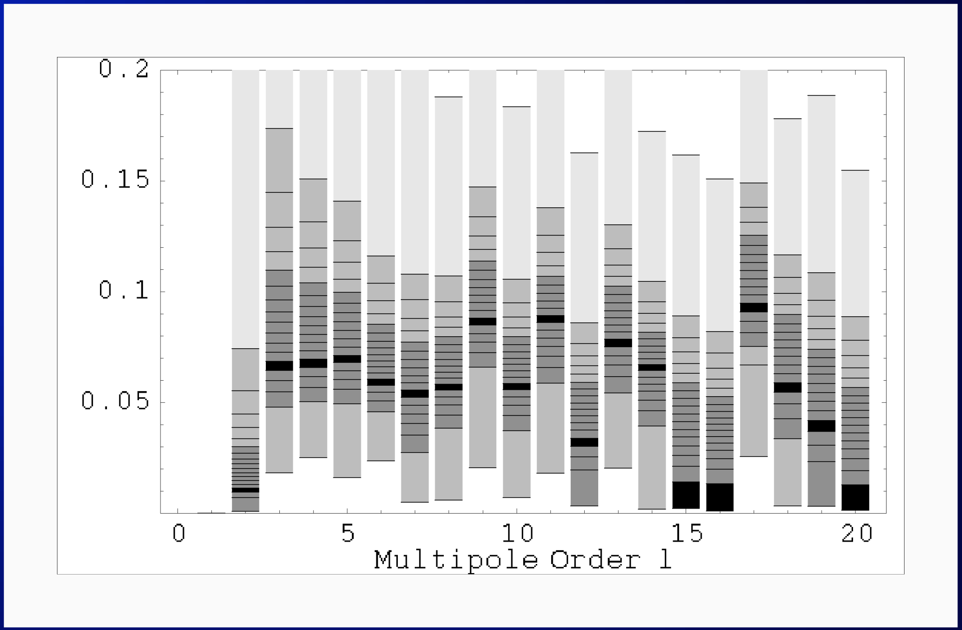
Wandelt, Larson, Lakshminarayanan (2004)

COBE-DMR power spectrum estimation

Kris Górski's last word on maximum likelihood DMR C_l



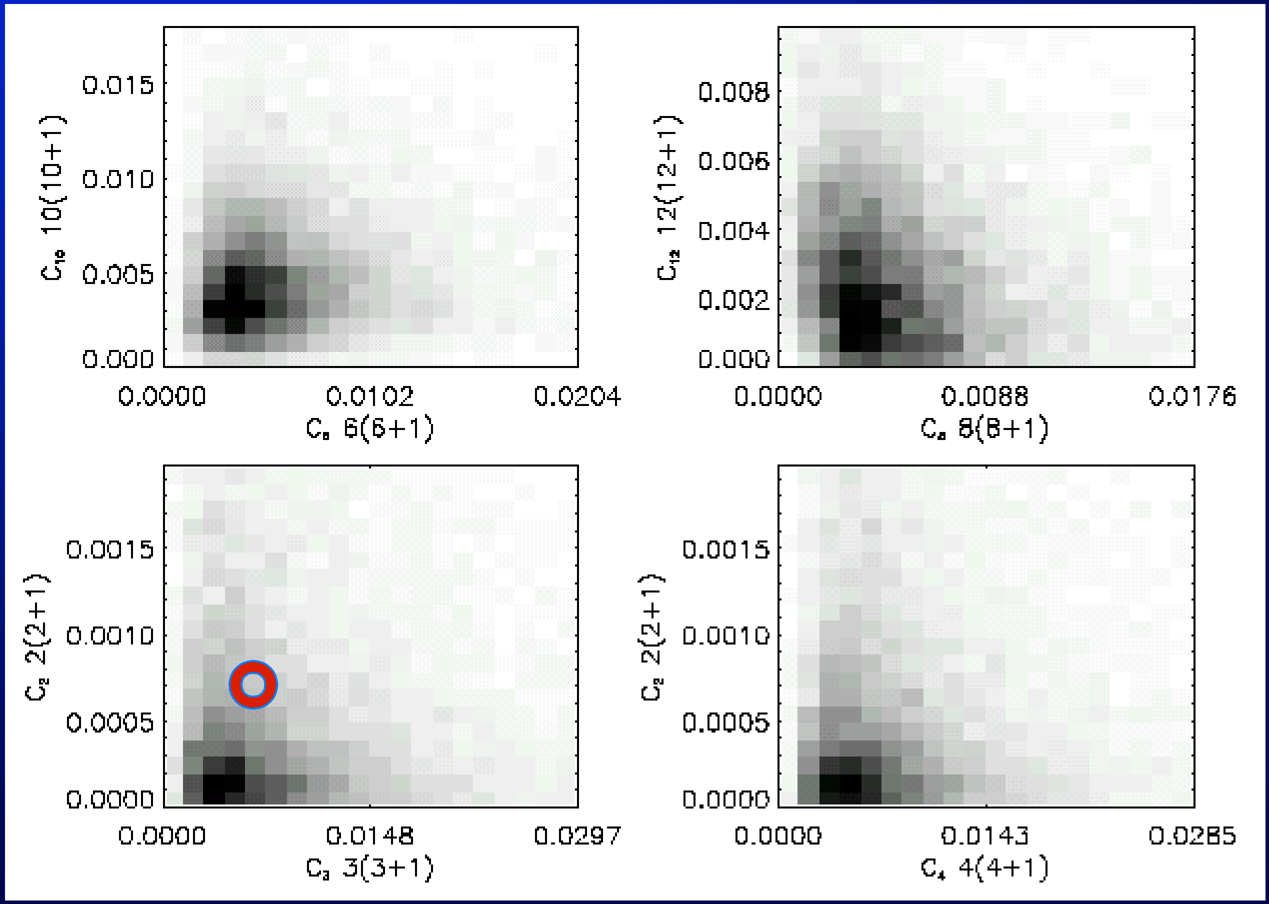
MAGIC results.



Note: left plot shows **conditional** error bands for each C_l (keeping all other C_l fixed at their ML values) – ours shows **marginalized** errors (for the first time for COBE!). The Gibbs sampler captures the full multivariate non-Gaussian structure of the CMB .

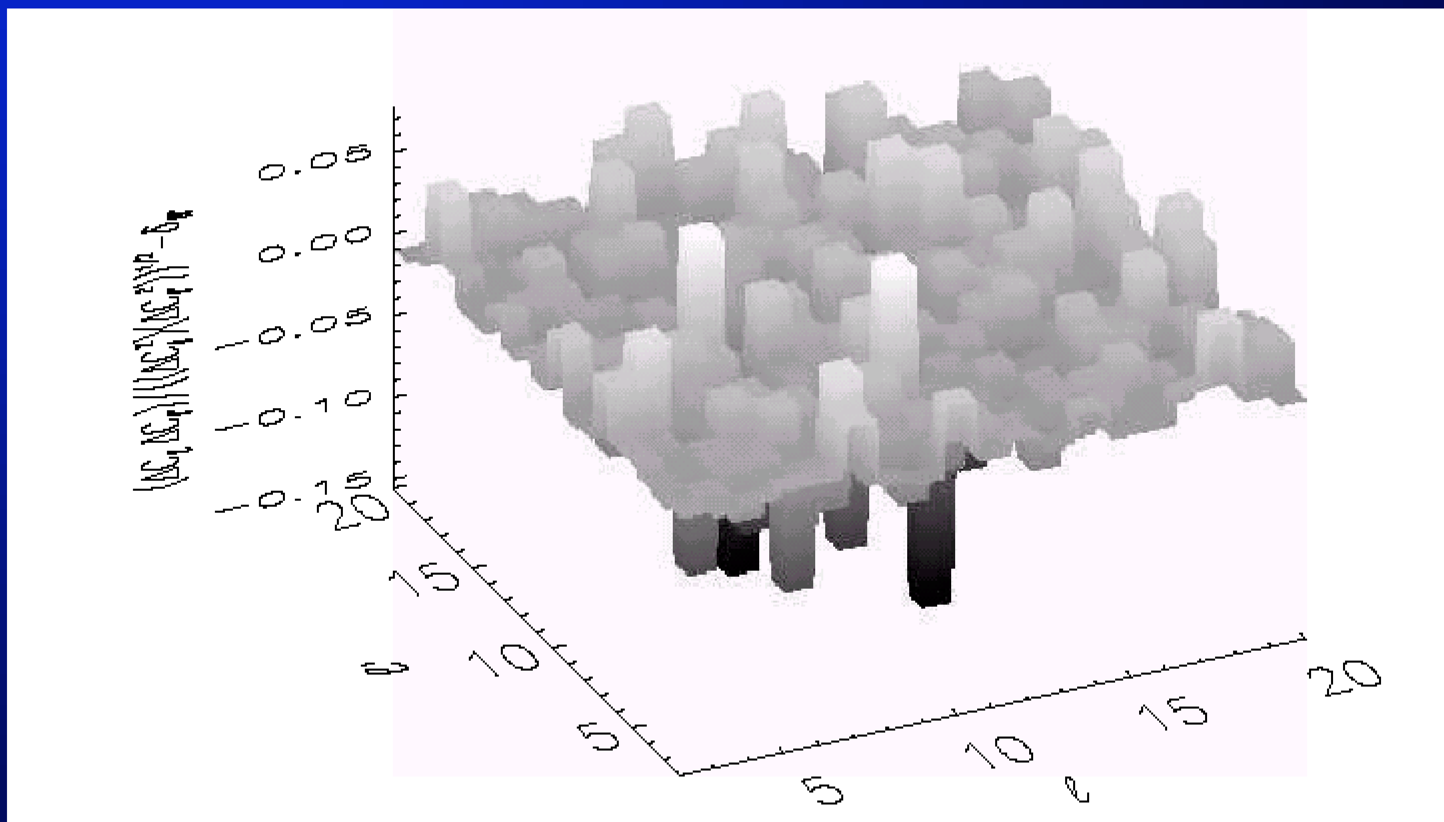
Wandelt, Larson, Lakshminarayanan (2004)

2-D marginalized posteriors from COBE-DMR



Wandelt, Larson, Lakshminarayanan (2004)

C_l Correlation matrix



Wandelt, Larson, Lakshminarayanan (2004)

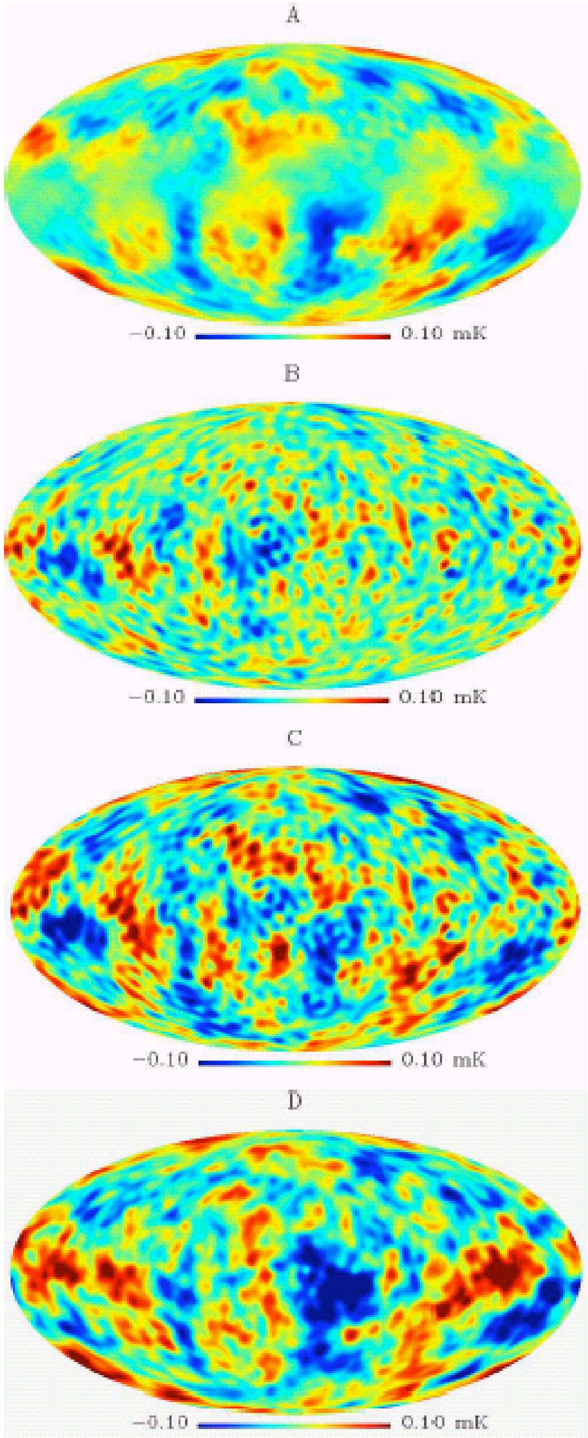
DMR generalized Wiener Filter

Example DMR fluctuation map

One pure signal sky allowed by DMR data

WMAP ILC smoothed to 5 degrees

Wandelt, Larson, Lakshminarayanan (2004)



Bayesian WMAP Analysis

Self-consistent inclusion of stochastic foreground models (monopole, dipole, foreground dominated region)

I. O'Dwyer, et al., astro-ph/0407027, ApJ Letter

H.-K. Eriksen et al., astro-ph/0407028, ApJ Supp.

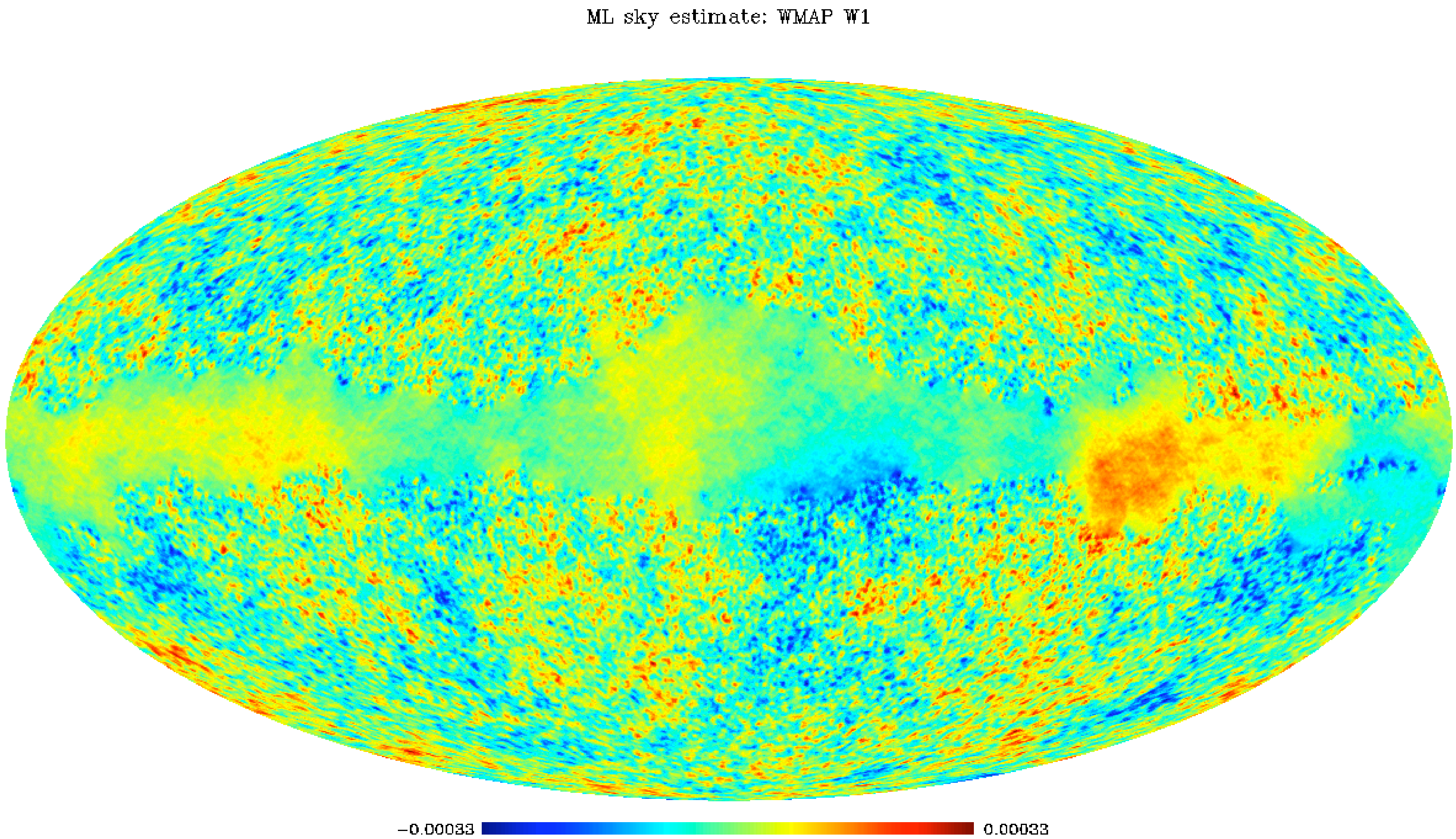
M. Chu et al., astro-ph/0411737, PRD

Collaborators

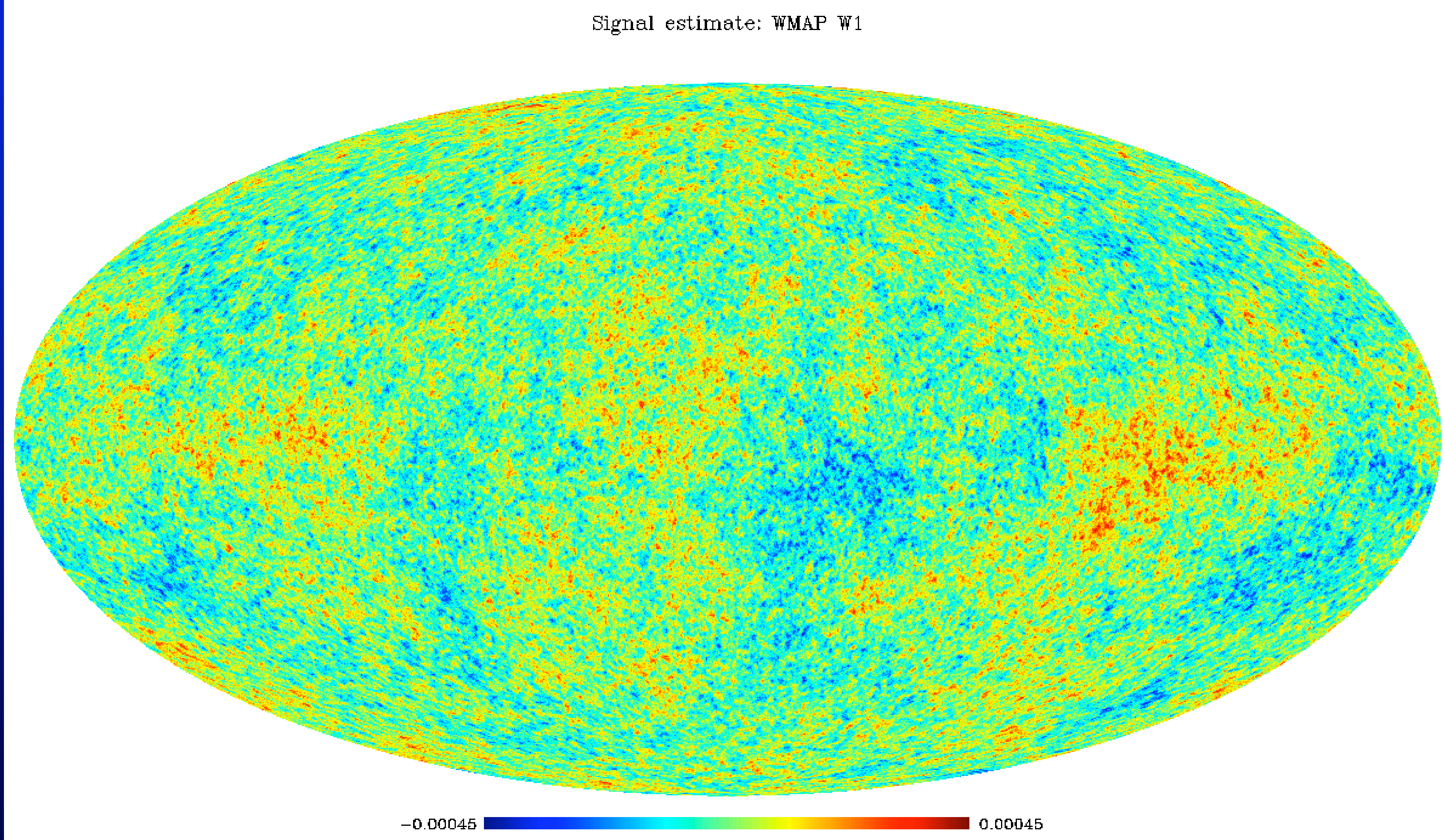
- Ian O'Dwyer, David Larson (UIUC)

- Hans-Kristian Eriksen, Per Lilje (Oslo)
- Mike Chu, Lloyd Knox (UC Davis)
- Jeff Jewell, Krzysztof Górski, S. Levin (JPL)
- Anthony Banday (MPA)

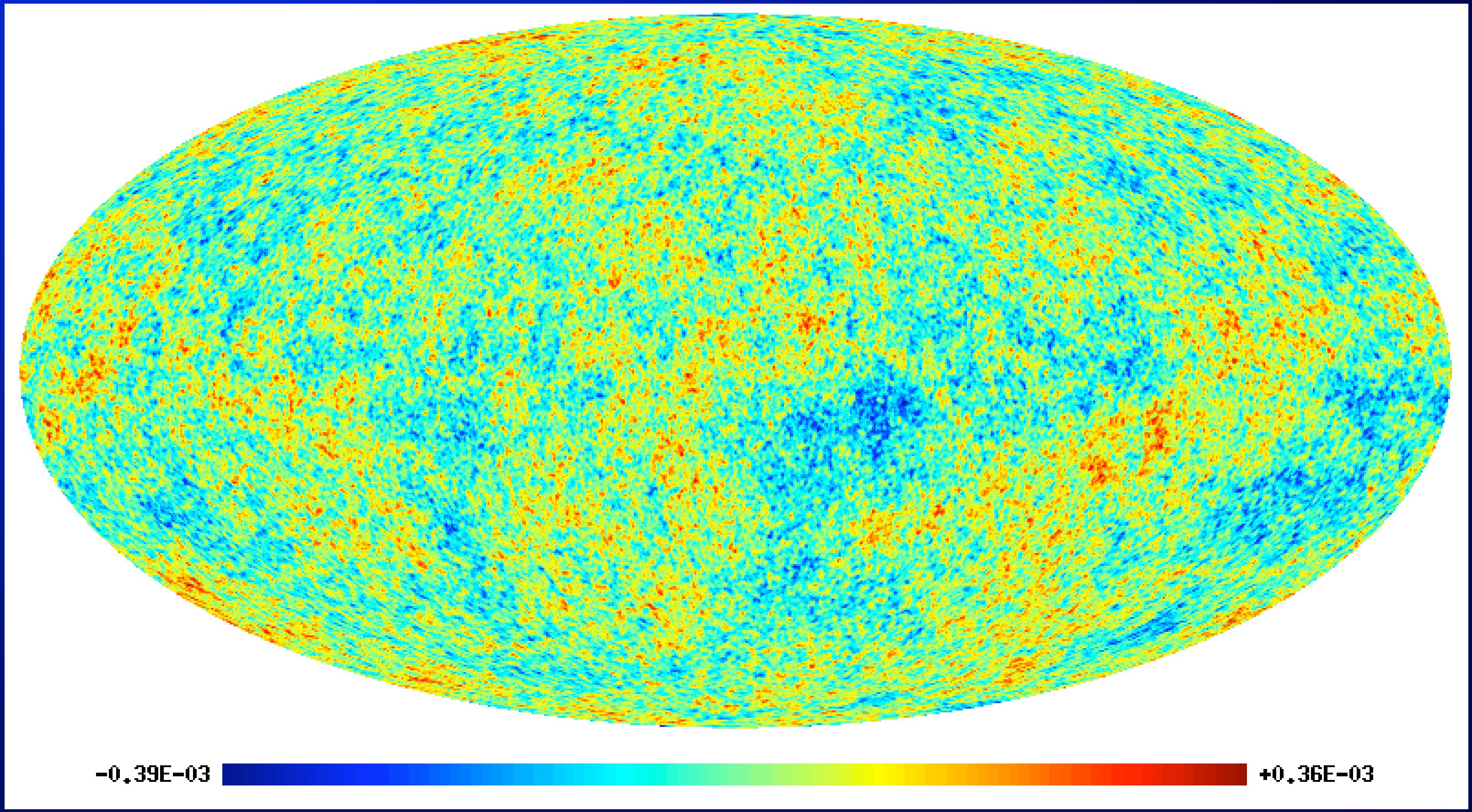
Wiener filtered W1 channel



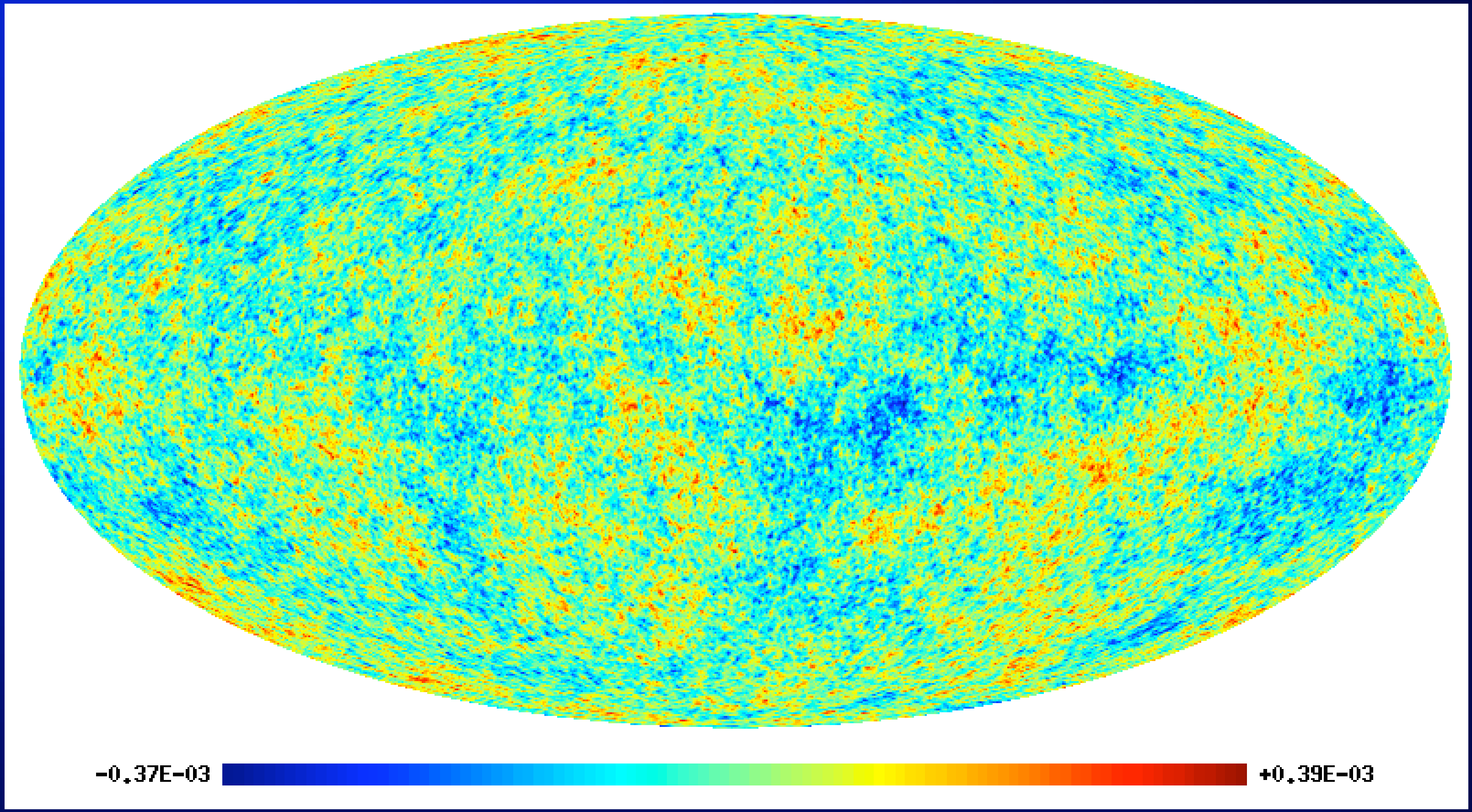
Constrained Realization of Pure CMB Sky based on WMAP W1 channel



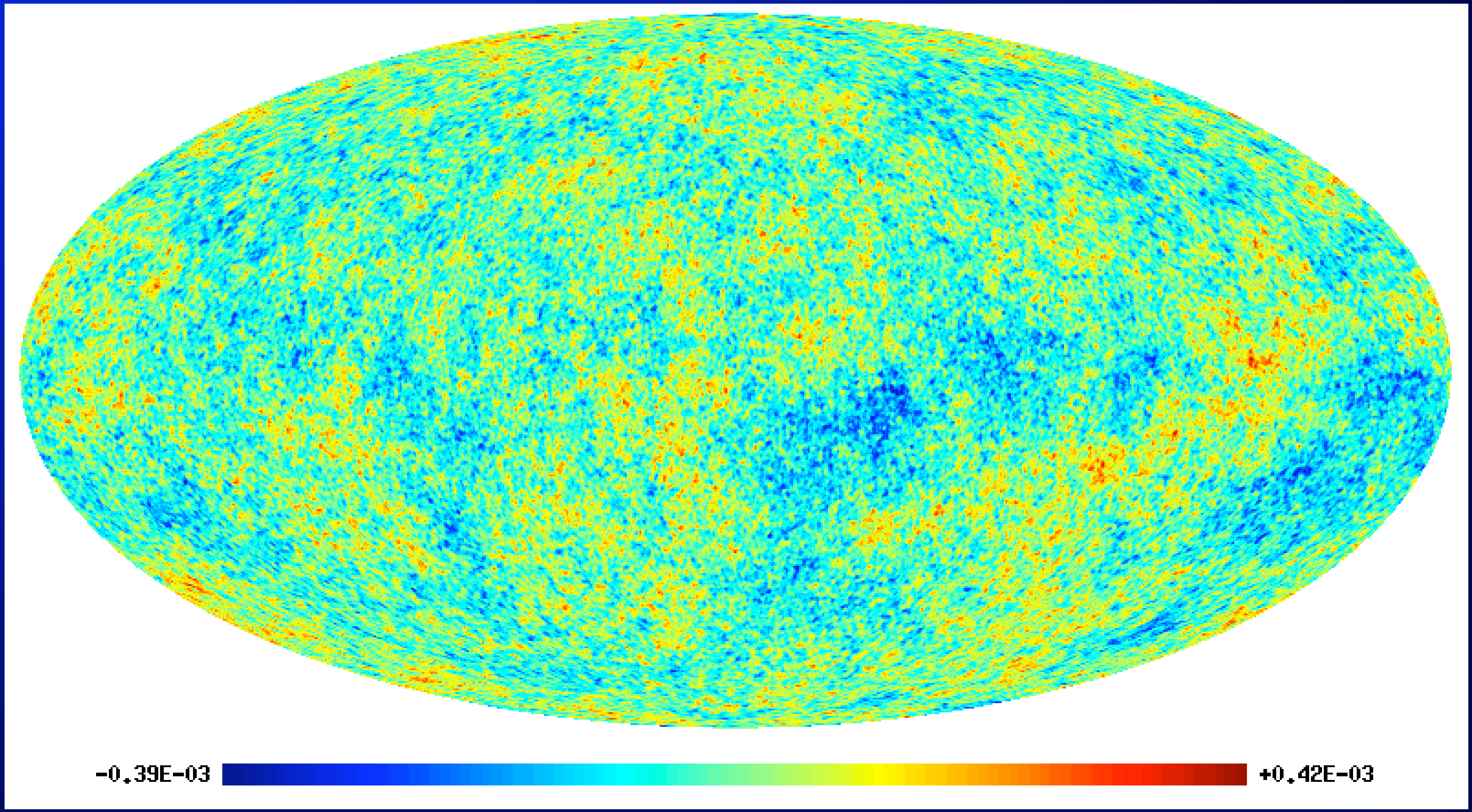
V band CMB sample 1



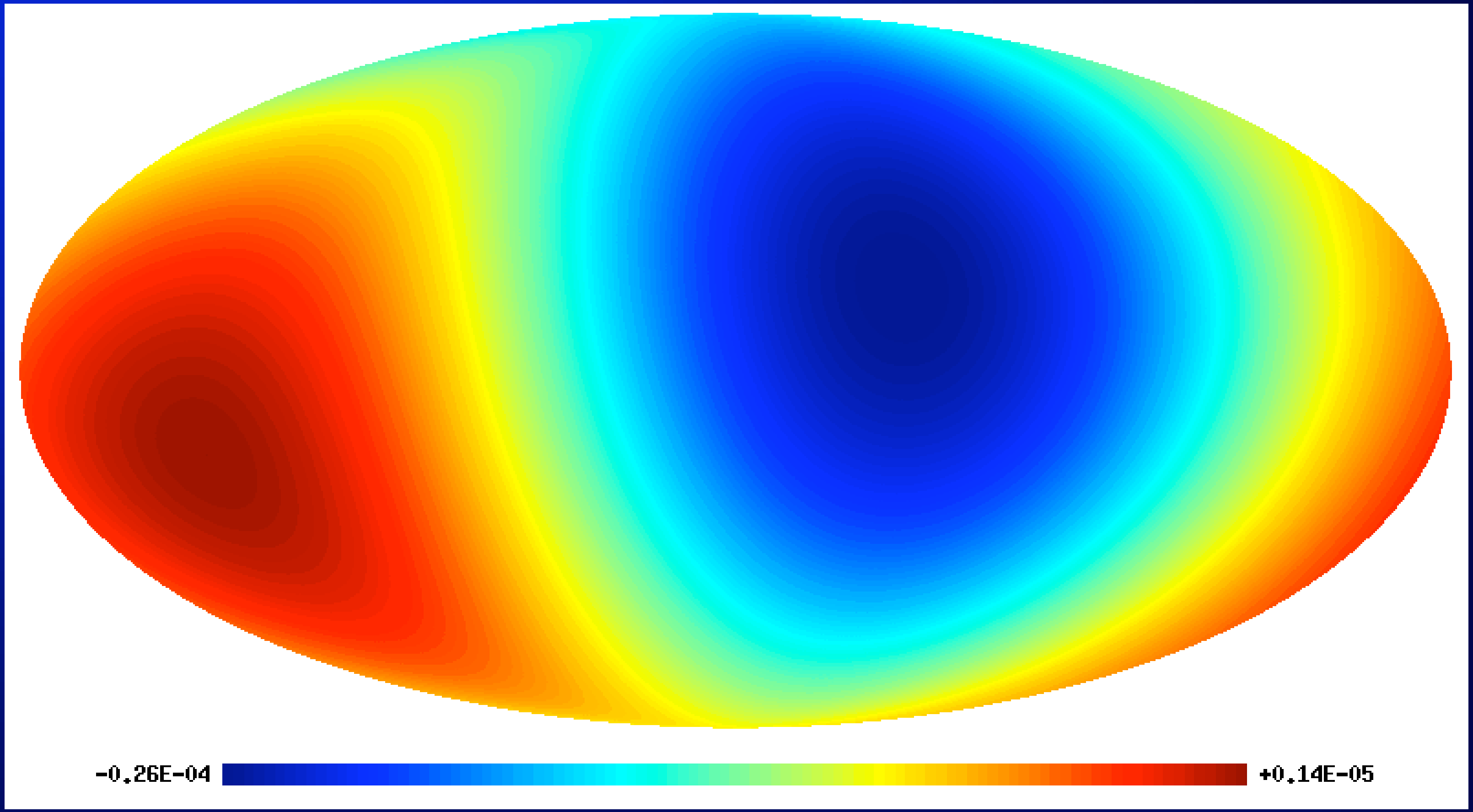
V band CMB sample 2



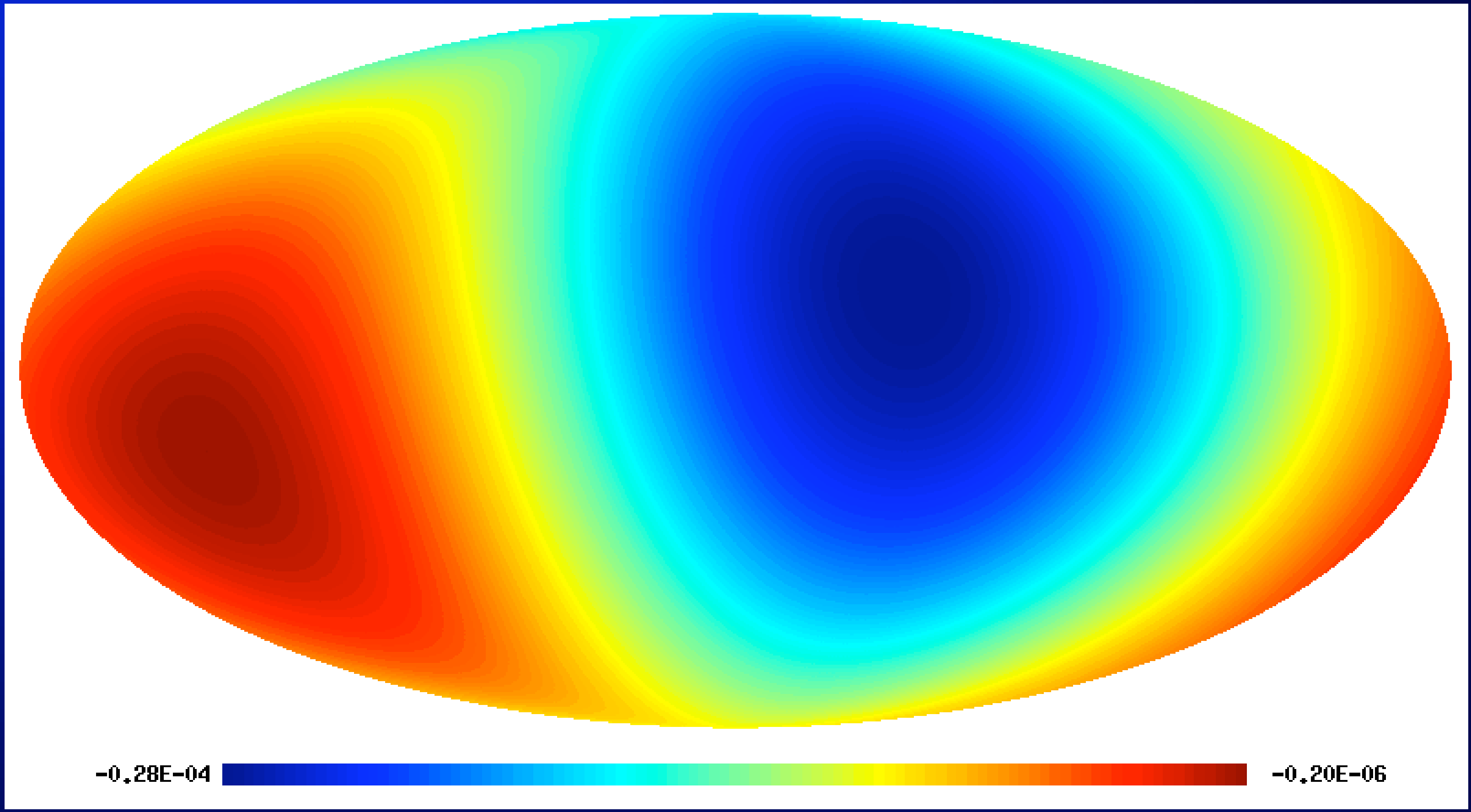
V band CMB sample 3



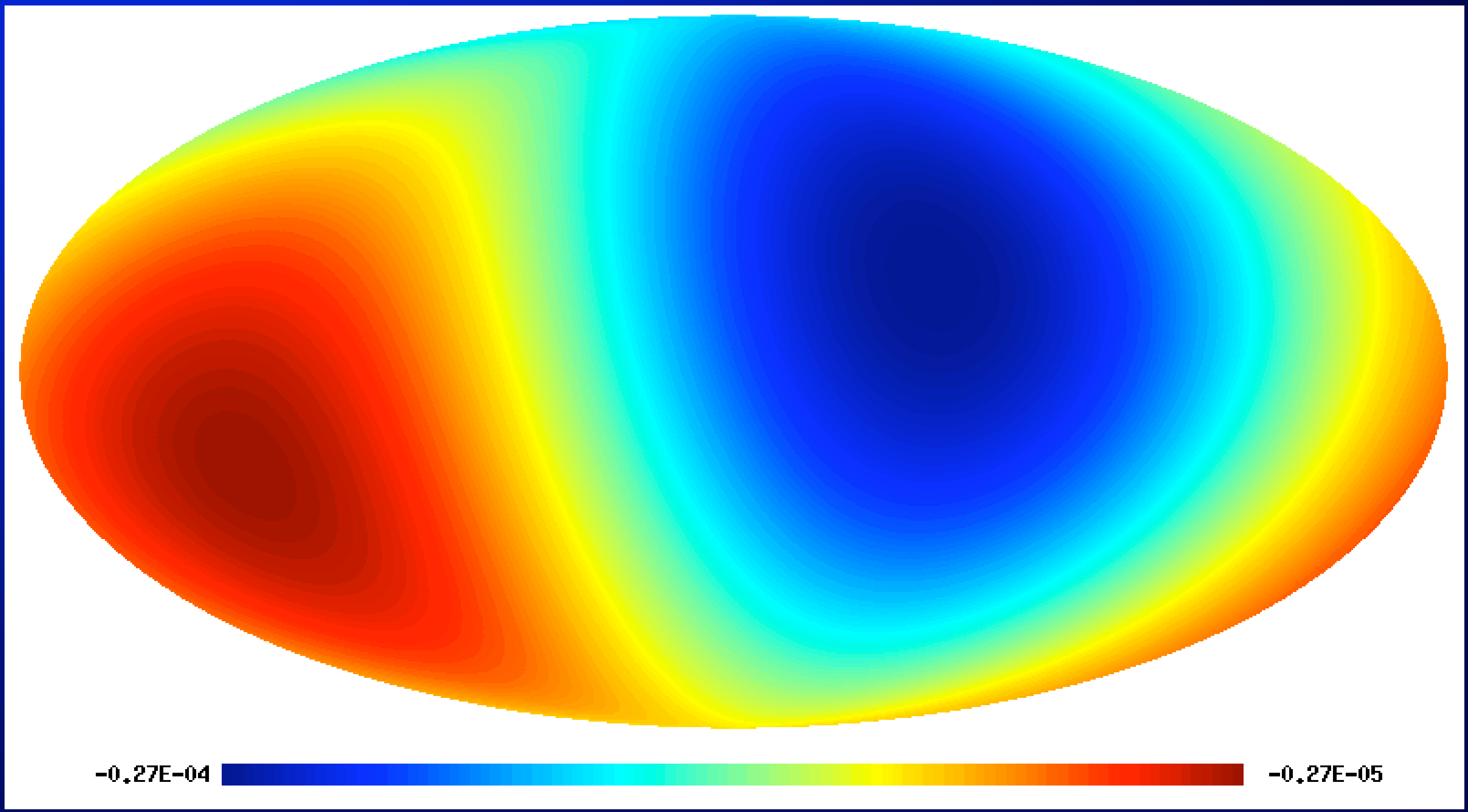
V band “monopole/dipole” 1



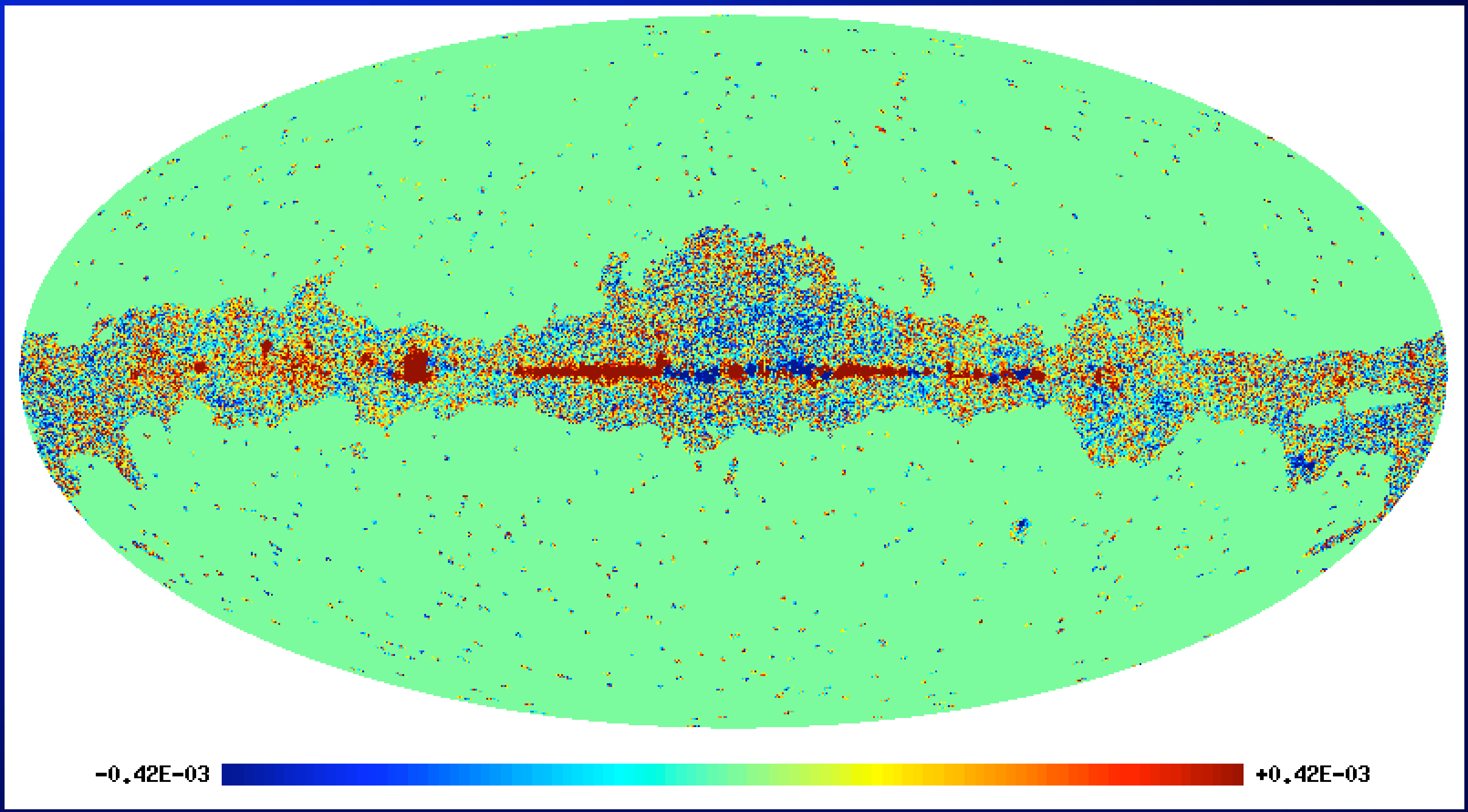
V band “monopole/dipole” 2



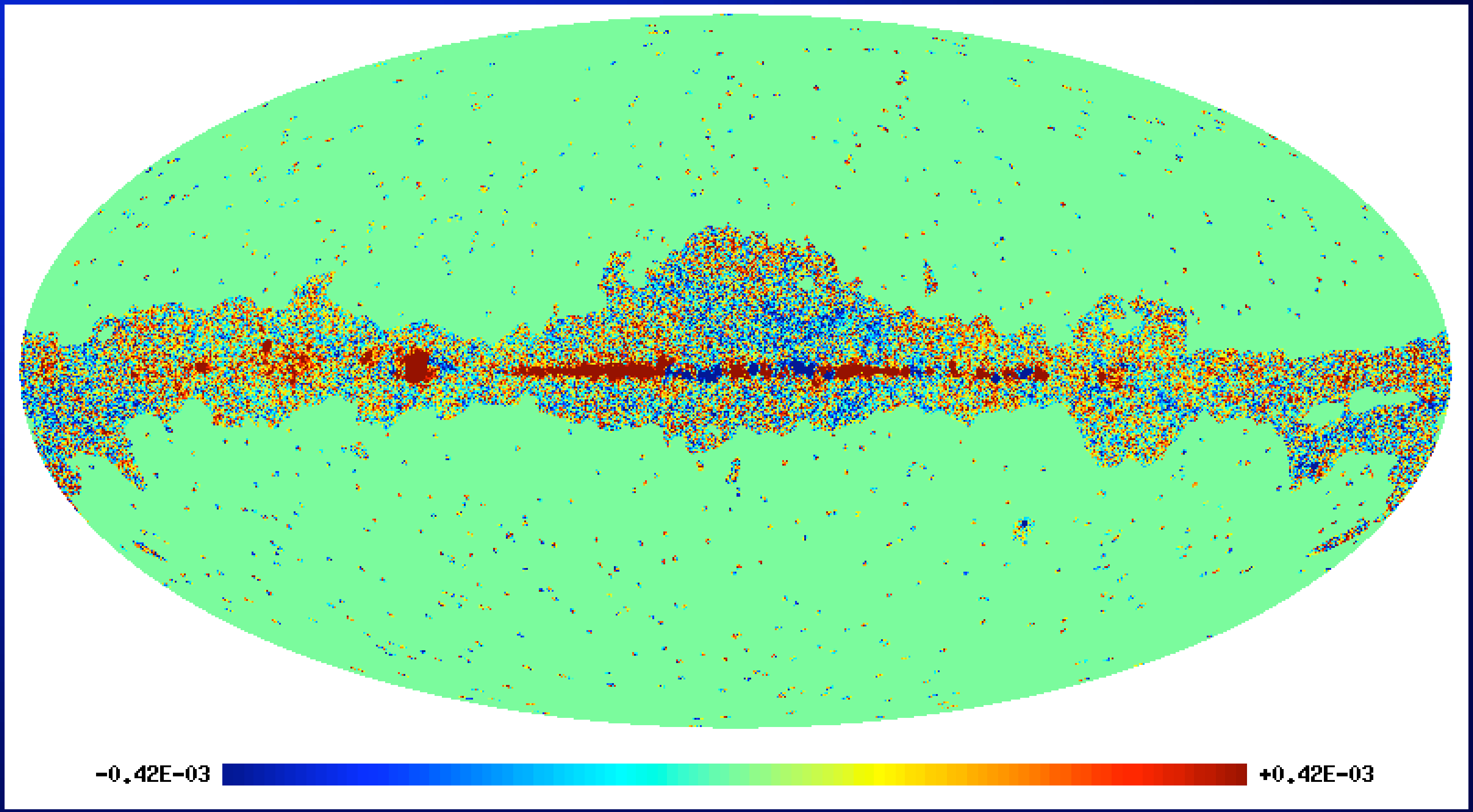
V band "monopole/dipole" 3



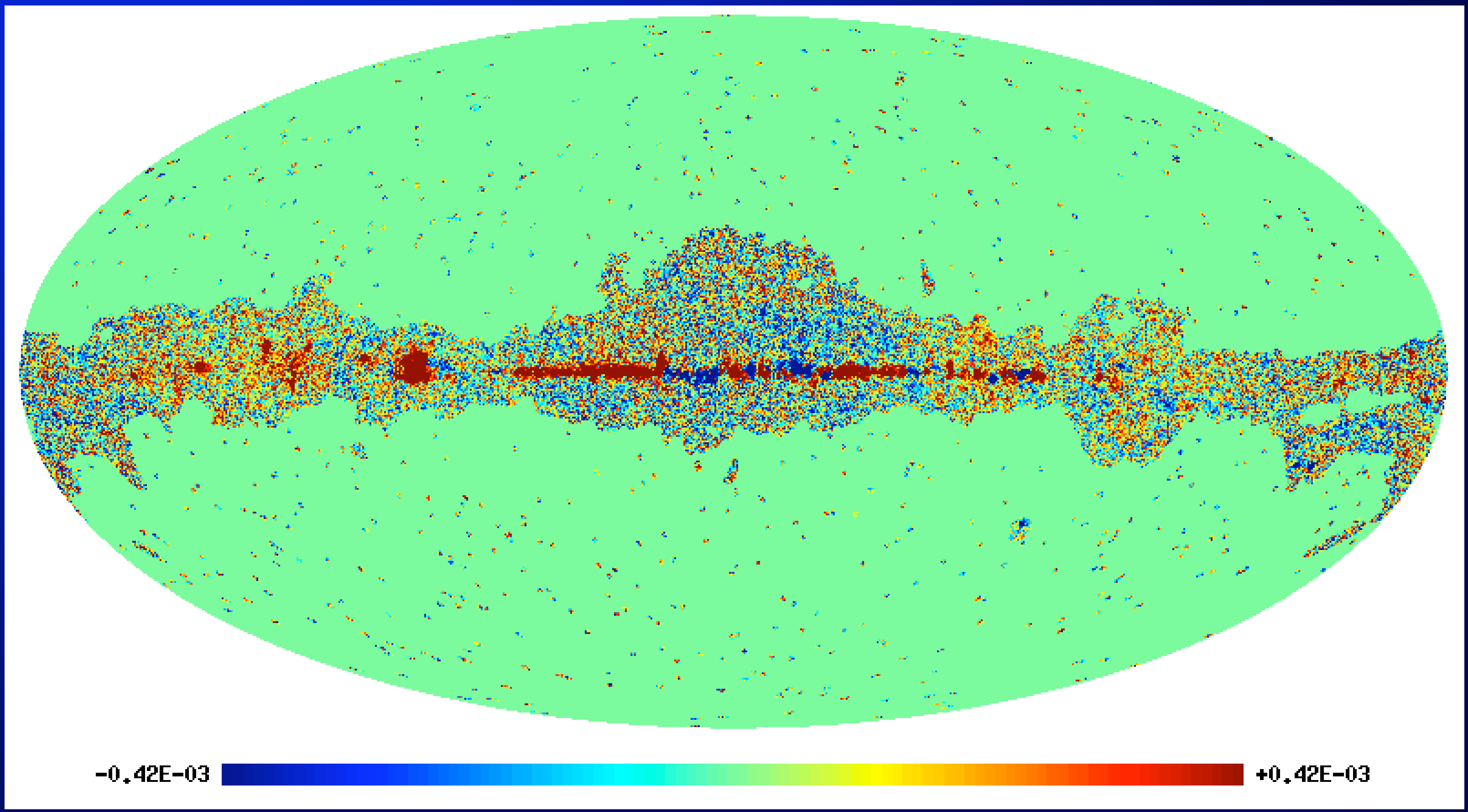
V band foreground sample 1



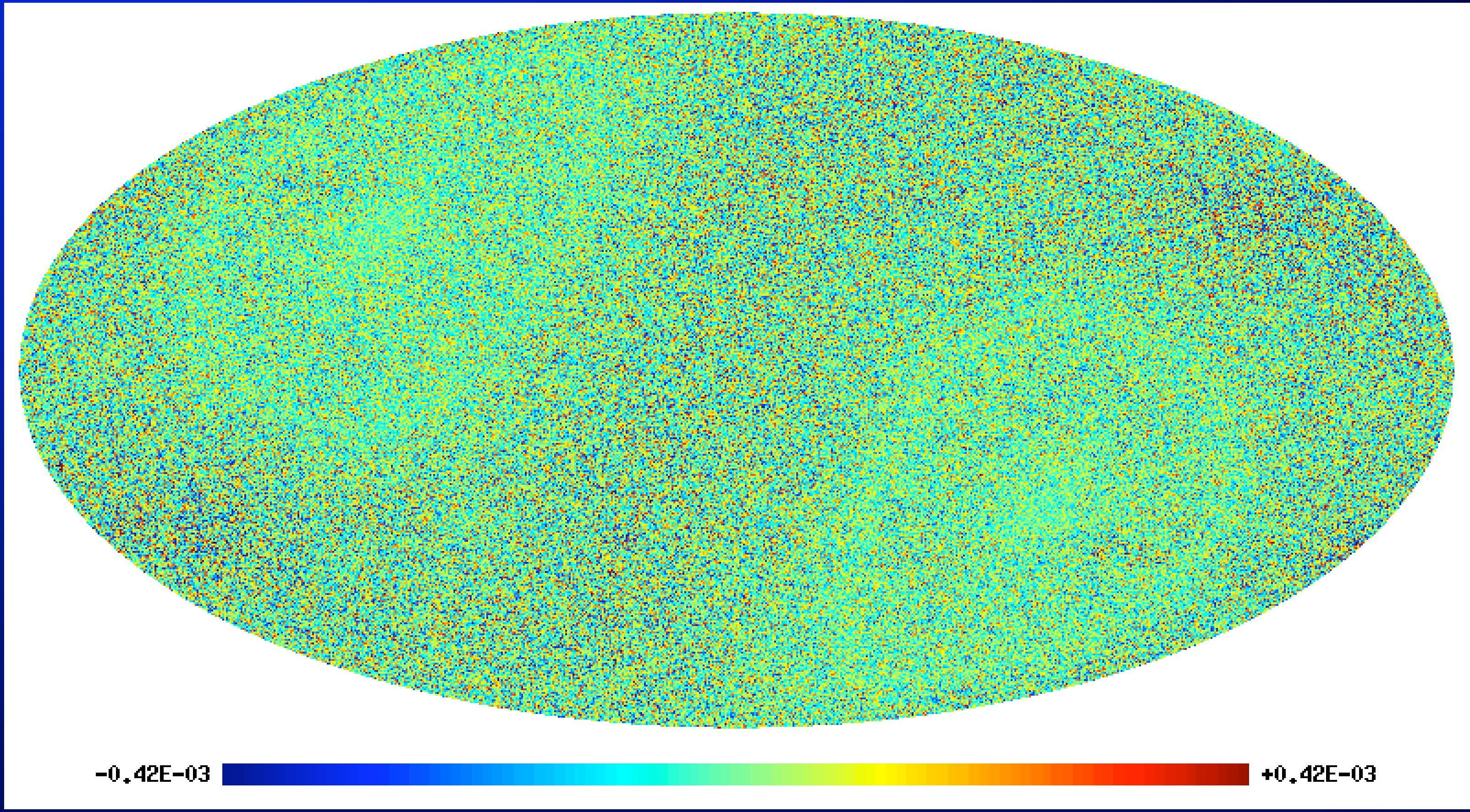
V band foreground sample 2



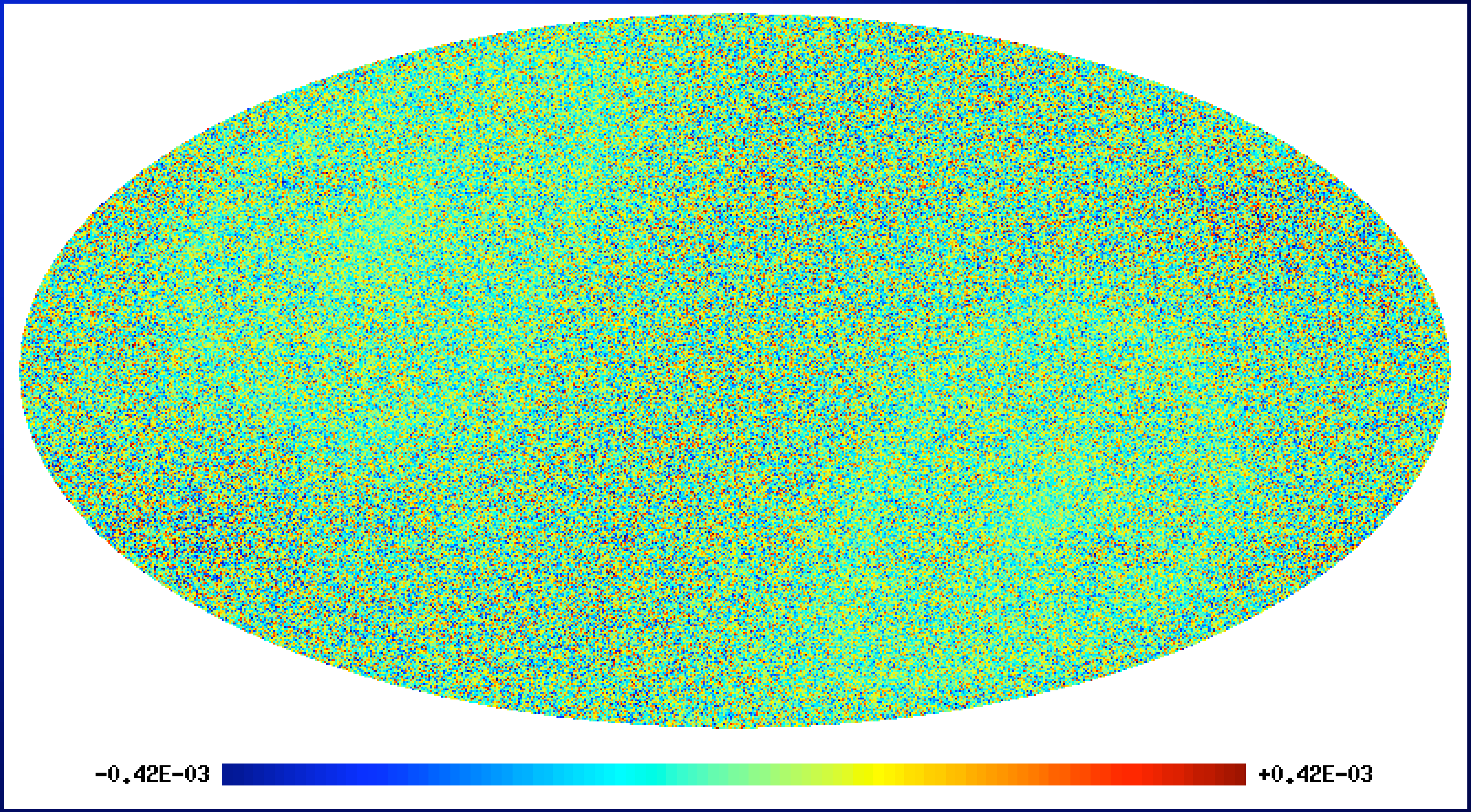
V band foreground sample 3



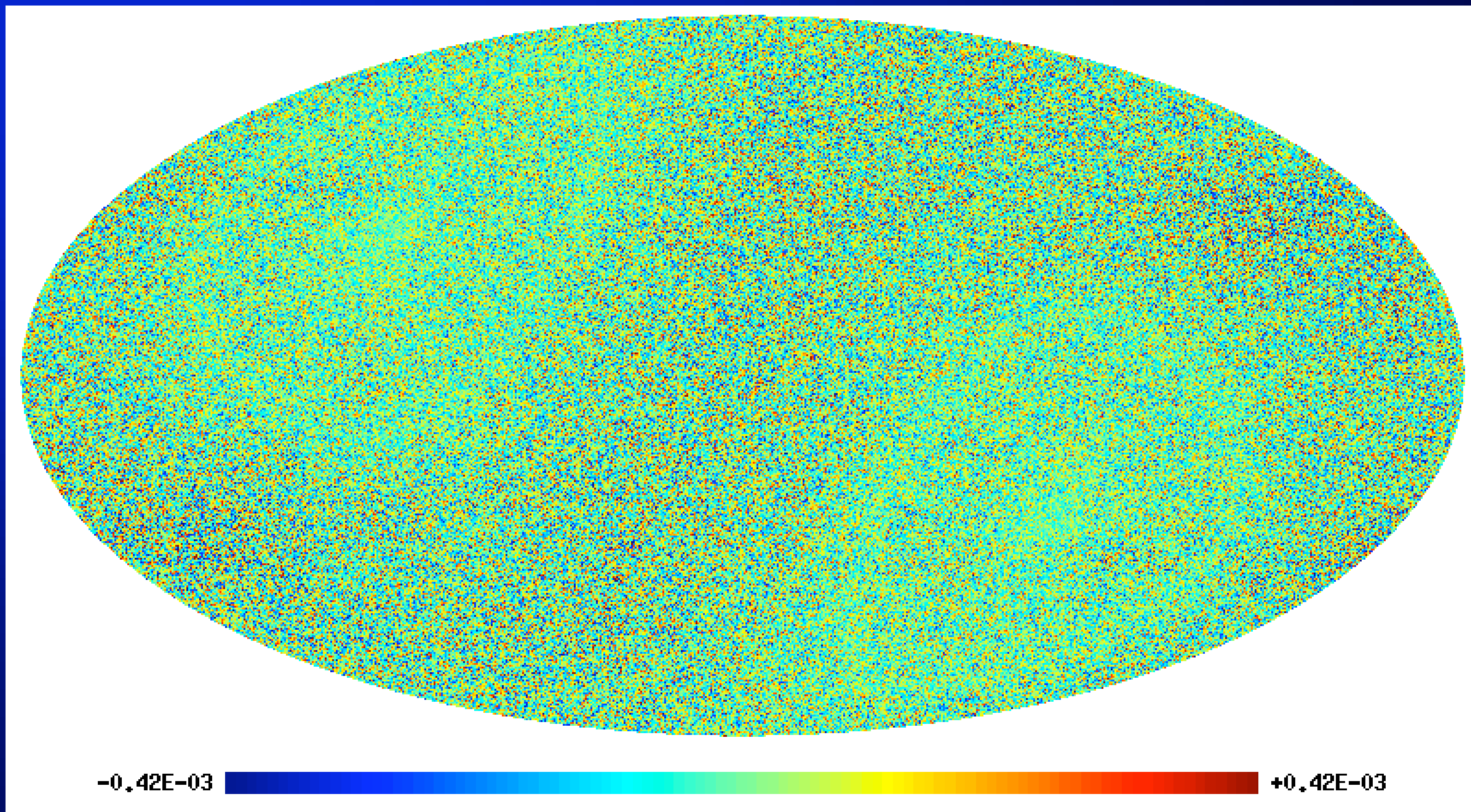
V band residual 1



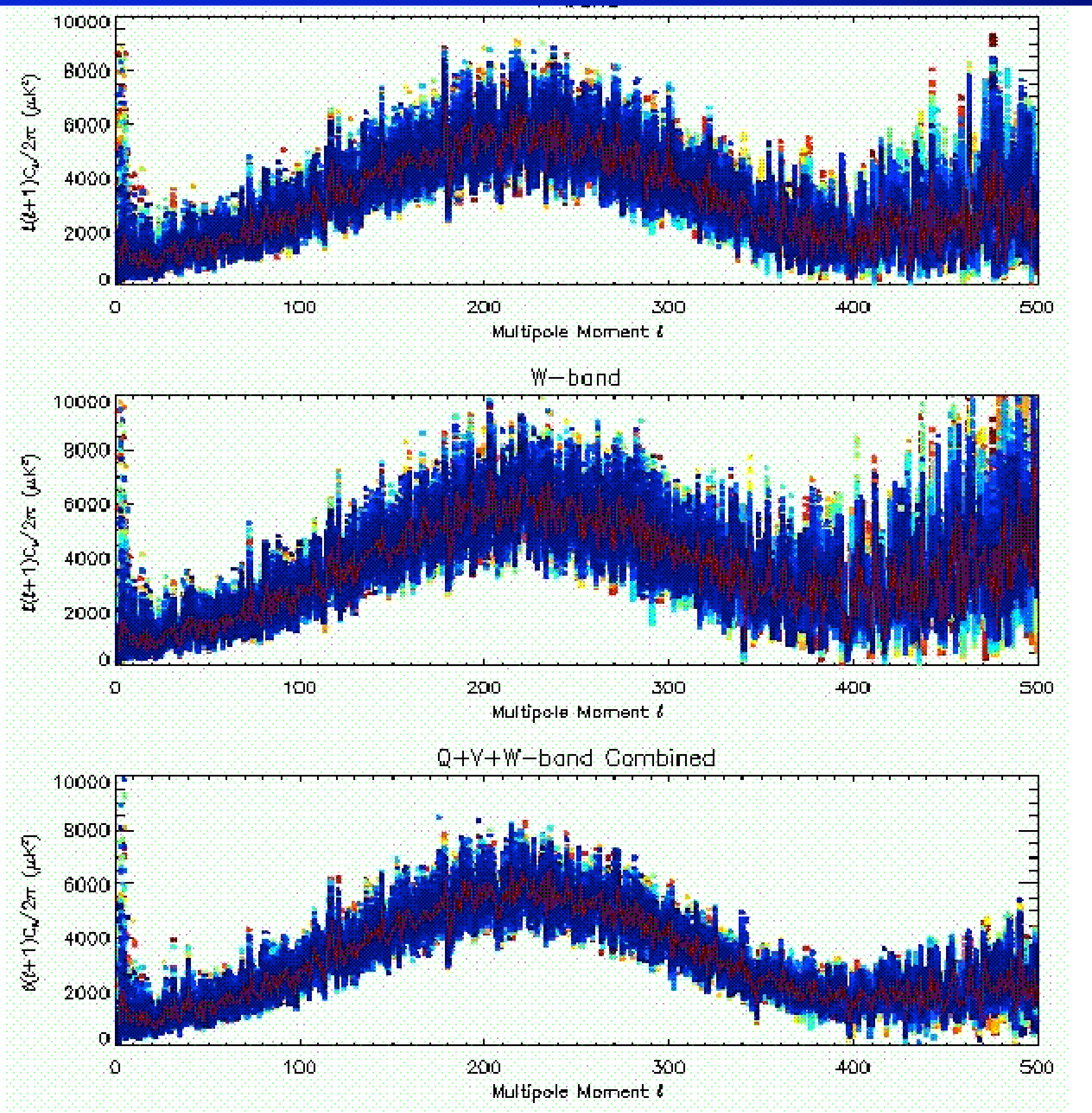
V band residual 2



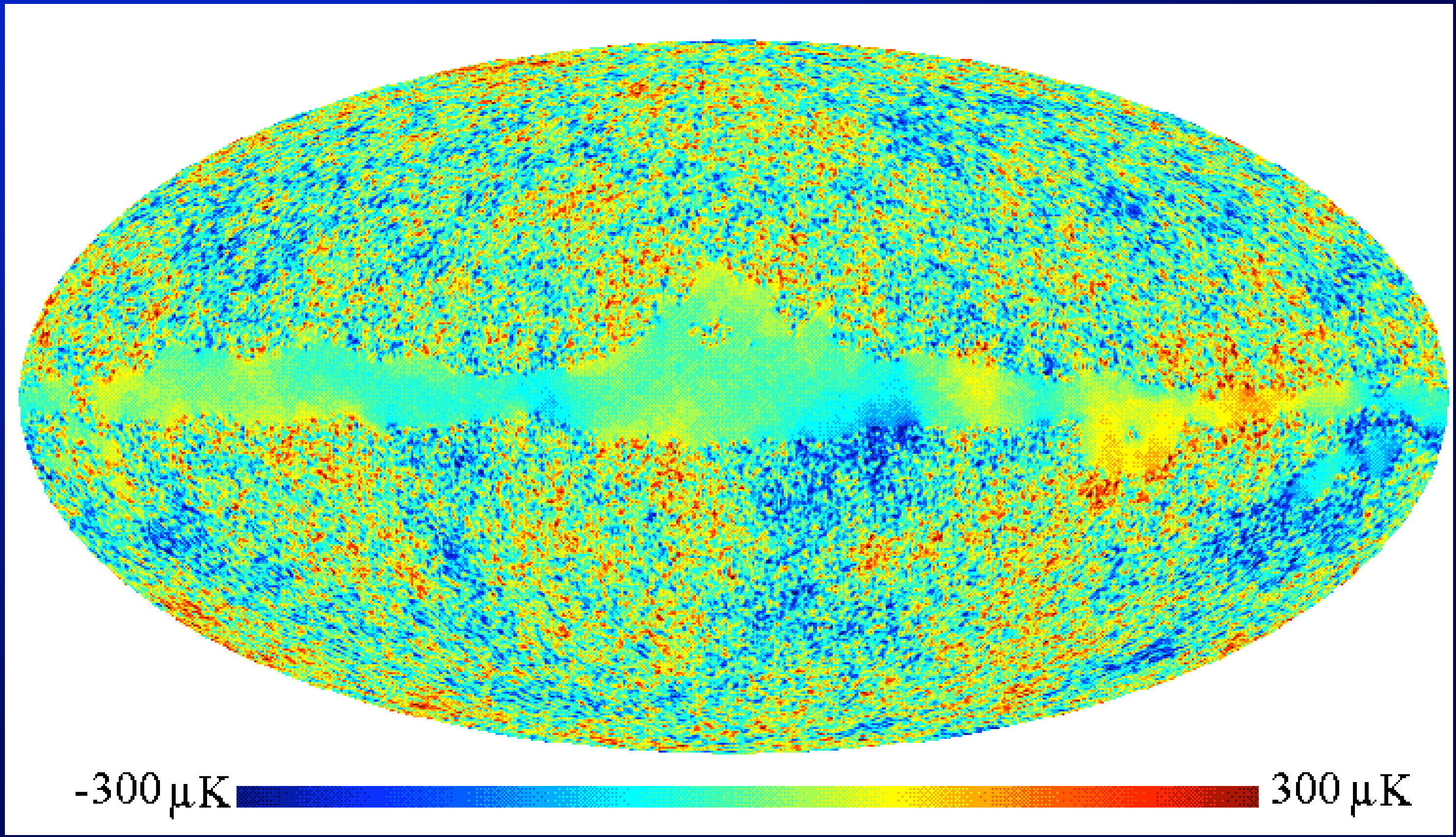
V band residual 3



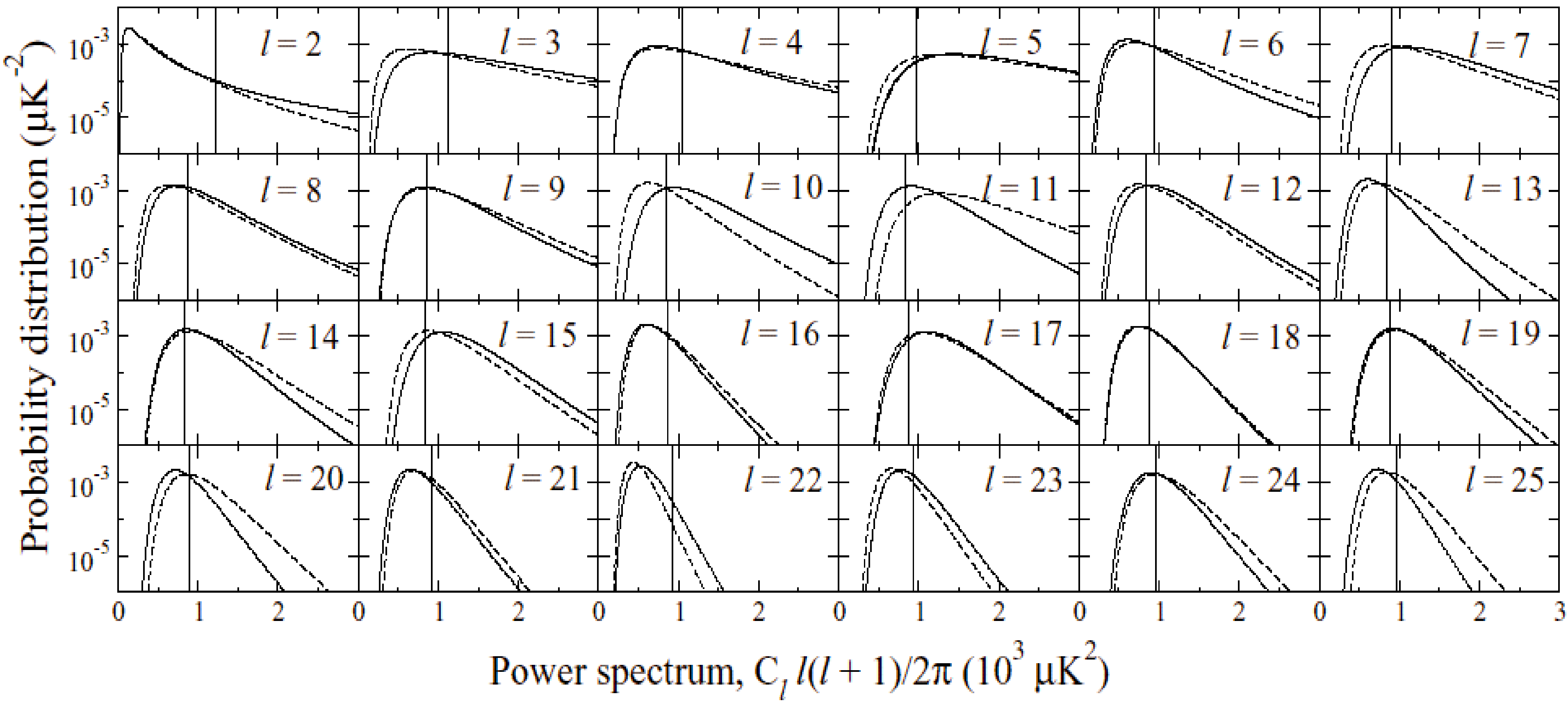
Power spectra from Bayesian Analysis of WMAP



Generalized Wiener Filtered WMAP (combining Q+V+W)

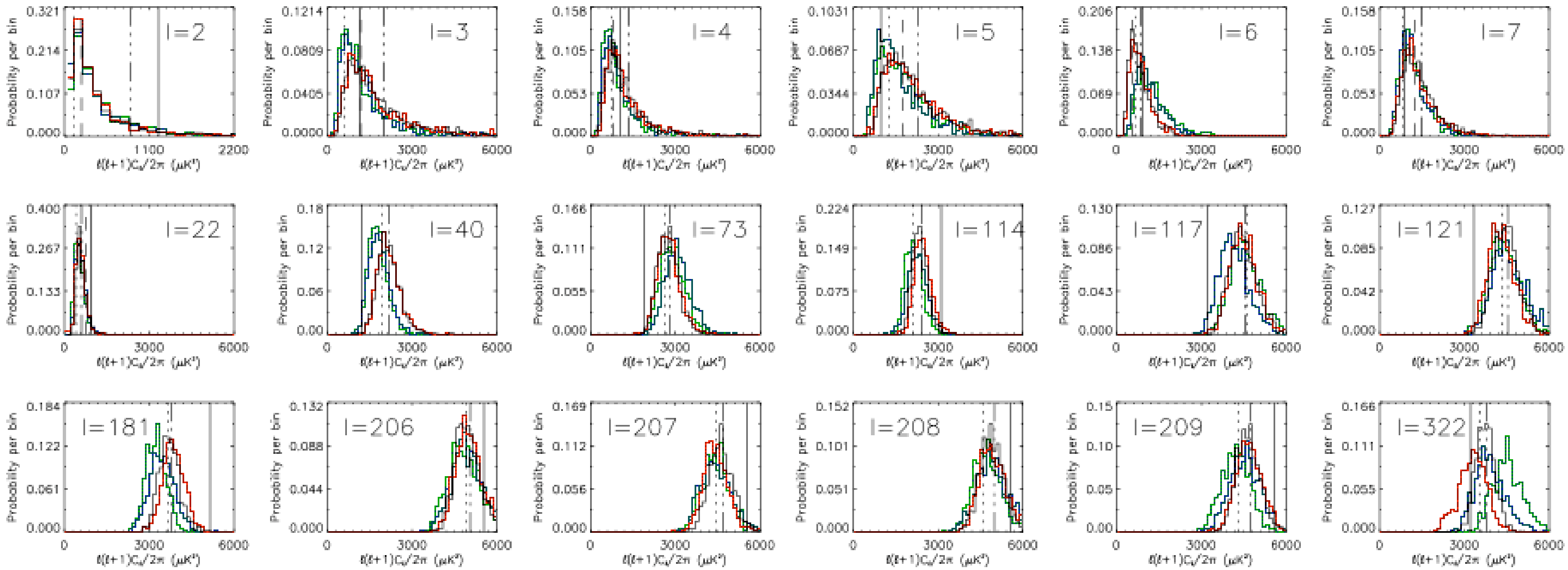


Comparison of low _ likelihood from WMAP analysis (dashed) and from Gibbs sampling (solid)



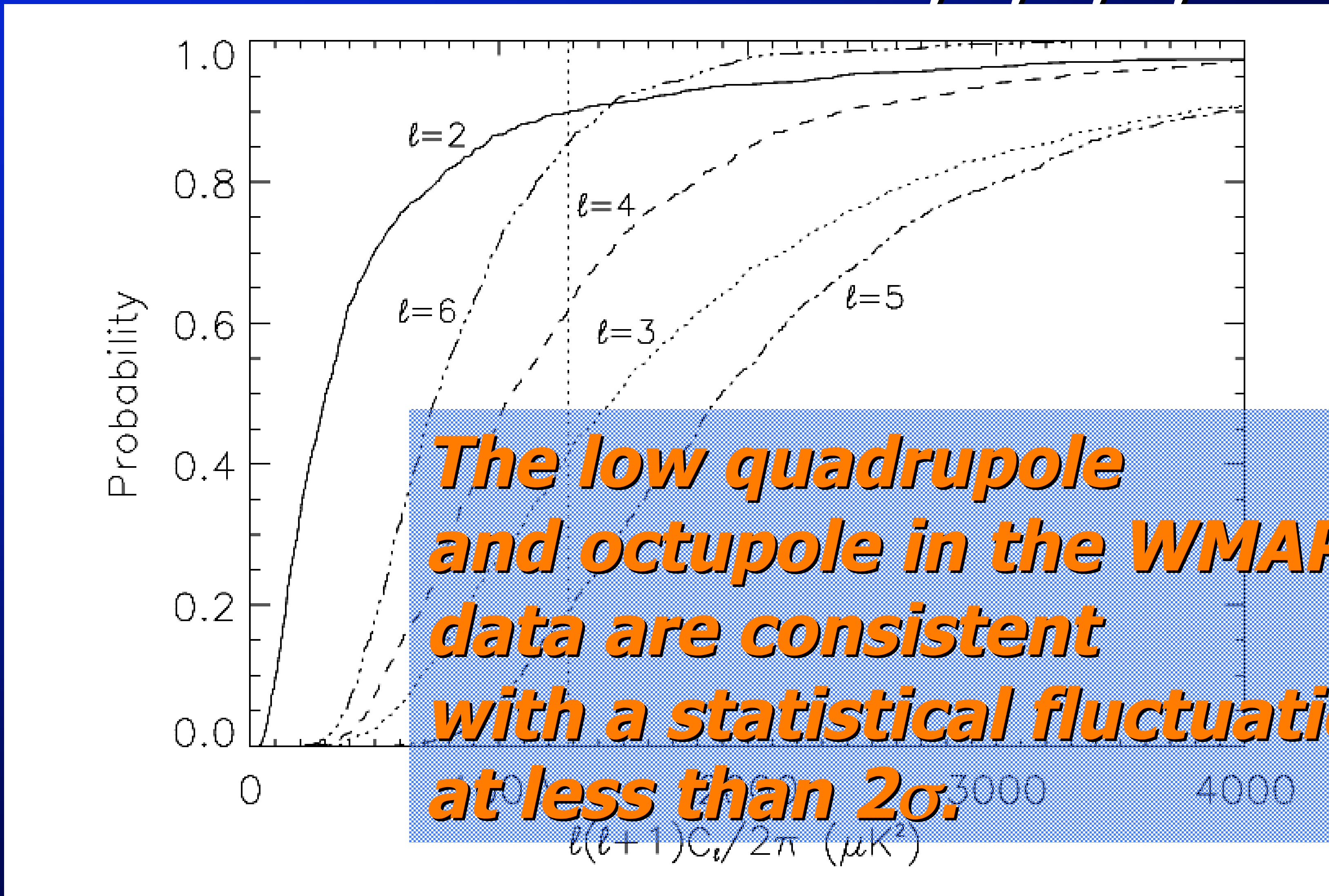
M. Chu et al (2005)

Marginalized posterior densities from WMAP



O'Dwyer et al. (2005)

Posterior CDFs for l=2,3,4,5,6



The low quadrupole and octupole in the WMAP data are consistent with a statistical fluctuation at less than 2σ.

O'Dwyer et al (2004)

Advantages of Gibbs Sampling

- Maps out the **full C_l likelihood** for temperature and polarization.
- Enables cosmological parameter estimation for polarization data without analytical approximation ansatz.

- **Signal map reconstruction** “for free” (non-linear Wiener filter)
- Very flexible treatment of **foregrounds** with full statistics of uncertainties in the separated components (O’Dwyer et al, in preparation)
- The real payoff from this technique lies in the future...

The Promise of Bayesian Analysis using Gibbs Sampling

- Global, joint inference of
  - Power spectra (T, E, B).
  - Signal maps (T, E, B)
  - Cosmological parameters from T, E, and B with full information on uncertainty
  - Instrument properties/calibration (noise, beam shape).
  - Foreground estimation and component separation.
  - Reconstruction of the lensing potential (difficult)
- Cross-correlation analysis with other probes (galaxy surveys and weak-lensing maps)
- Non-Gaussianity tests with explicit Gaussian prior!

Acronym?

- MAGIC (MAGIC Allows Global Inference of Covariance)
- GEM (Global Estimation Method) ?
- Bayesian Approach to Data Analysis of Spectral Signatures ?
- Your suggestion here...

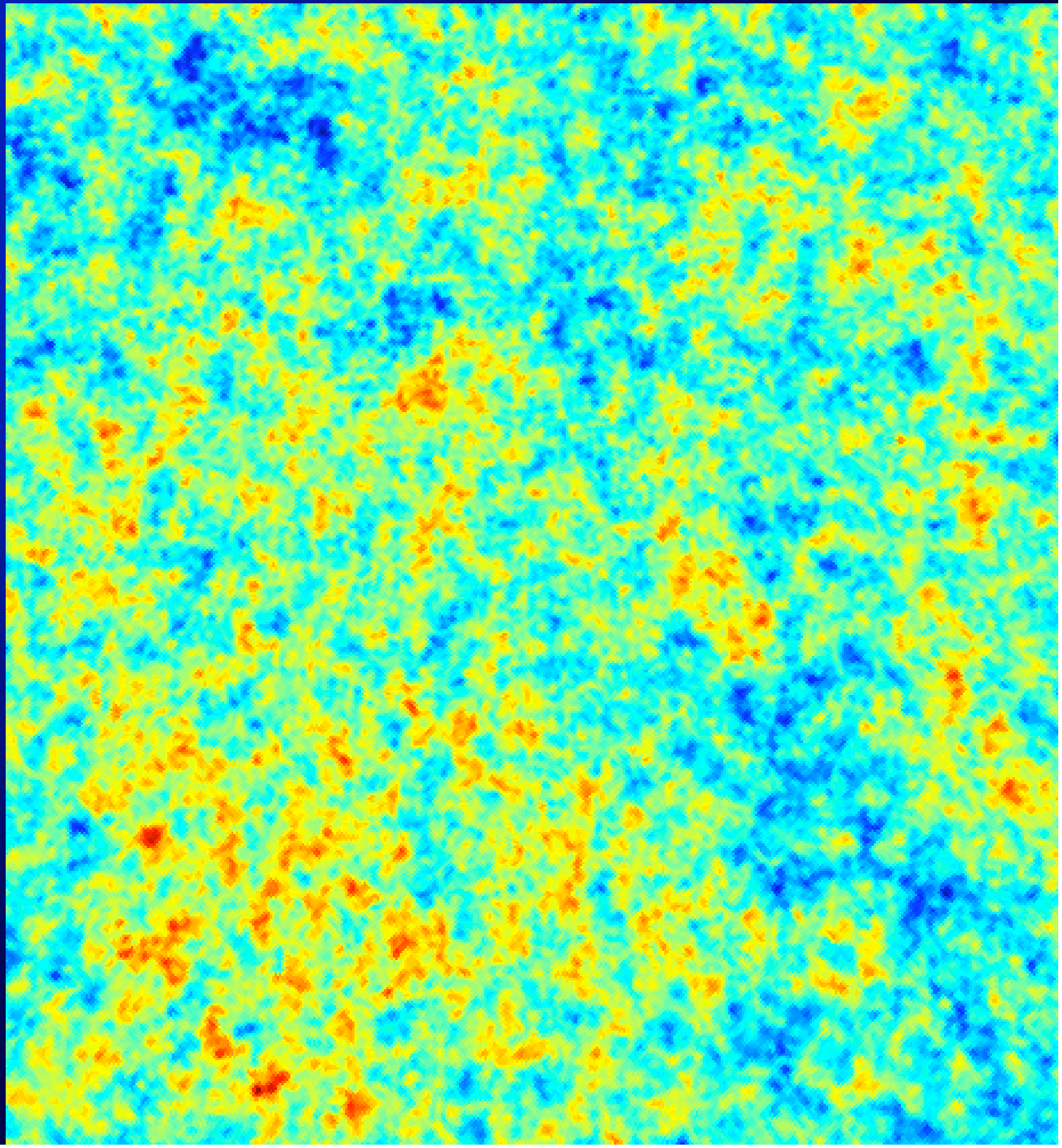
Into the Future

Beyond Concordance (I)

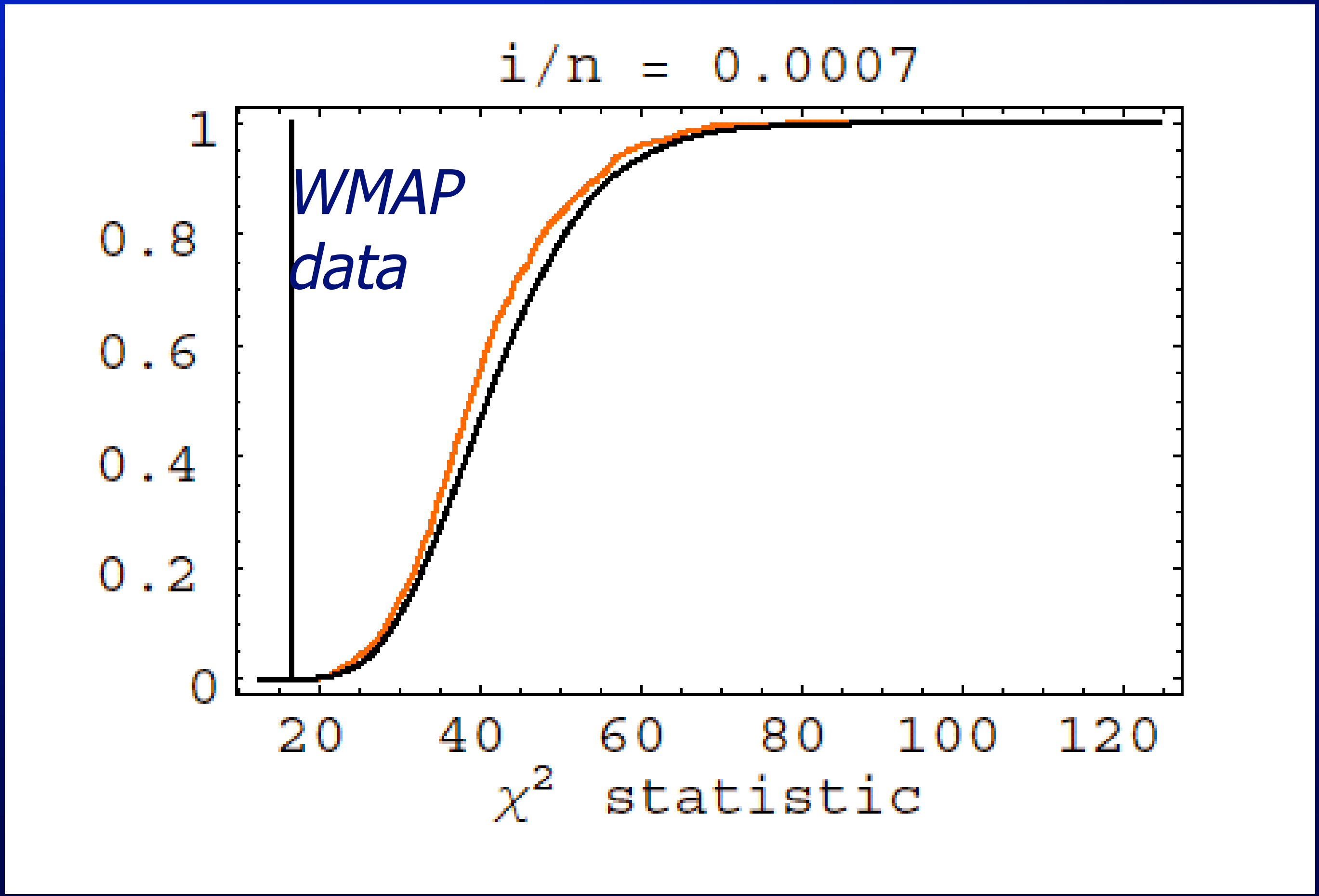
- The Initial Conditions:
  - Tests of non-Gaussianity
    - Frequentist blind tests (Bispectrum, Extrema, Wavelets, …)
    - Several caveats: non-dog problem, etc.

Example: Extrema Statistics (Larson and Wandelt 2004/5)

- 1-point and 2-point Properties of Maxima and Minima.
- Mean and variance of hotspot temperatures
- T-weighted and point-point corr. function



3-sigma detection in the T-weighted min-min correlation function on W-band



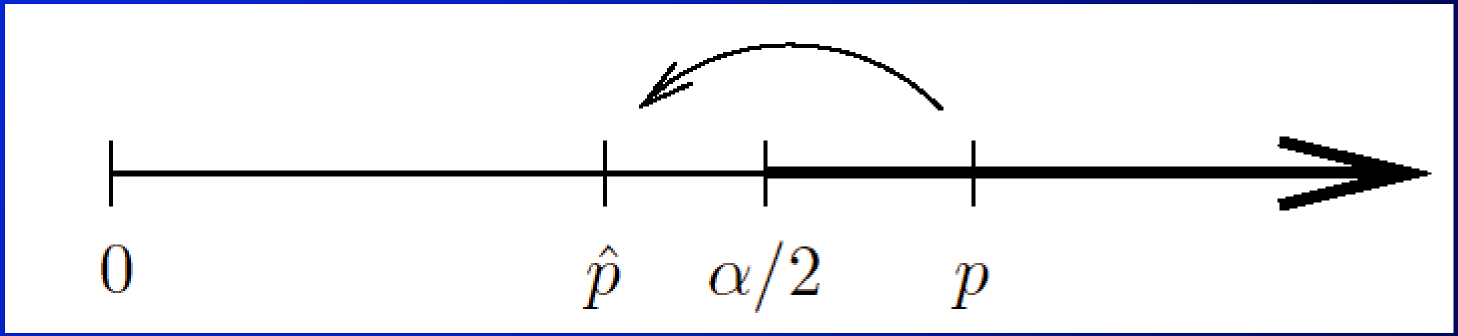
19,000 MCs

50 arcminute smoothing

3 sigma by our two-sided robust test

(Larson and Wandelt, astro-ph/0505046)

A robust statistical test

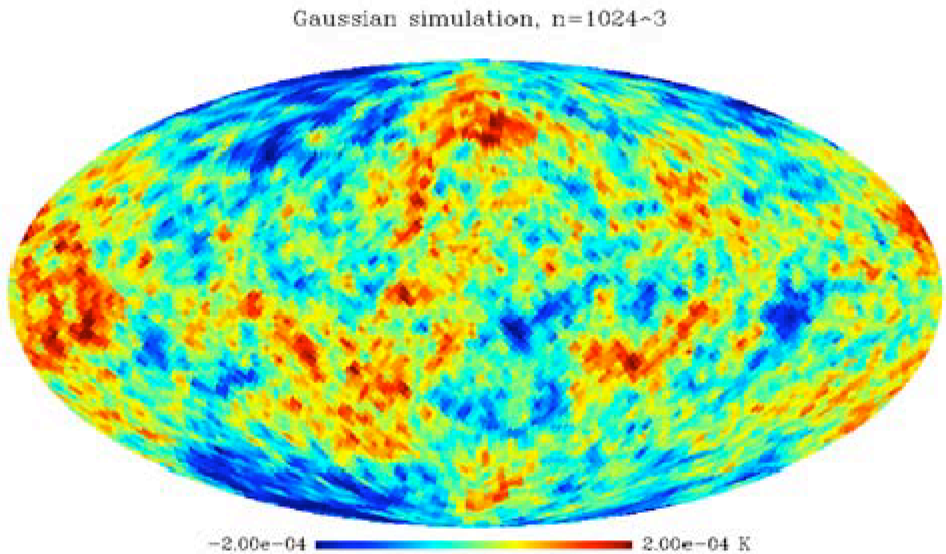


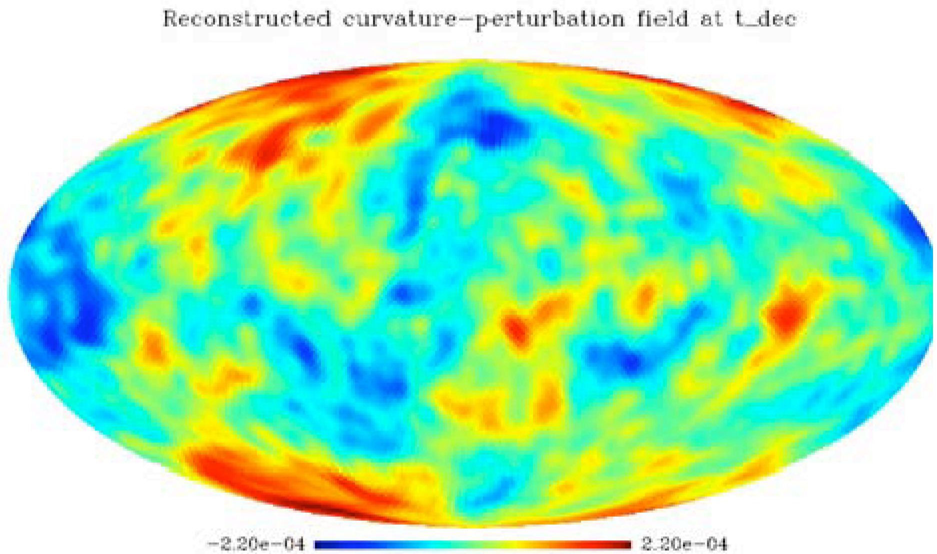
- Frequentist non-Gaussianity detections estimate the probability that the data is extreme, compared to Monte Carlo simulations. This is usually claimed as the significance of the test.
- However, the danger exists of detecting a statistical fluctuation in the MC instead of an actual anomaly. This leads to a false discovery.
- We define a statistical test that bounds the risk of false discovery to the same level as the claimed significance of the result.
- Implemented as public domain code "**`facts`**"
  - see Larson and Wandelt astro-ph/0505046

Beyond Concordance (II)

- The Initial Conditions:
  - Tests of non-Gaussianity
    - Frequentist blind tests
  - Reconstructing primordial scalar perturbations

Reconstructing the gravitational potential at last scattering (T only)



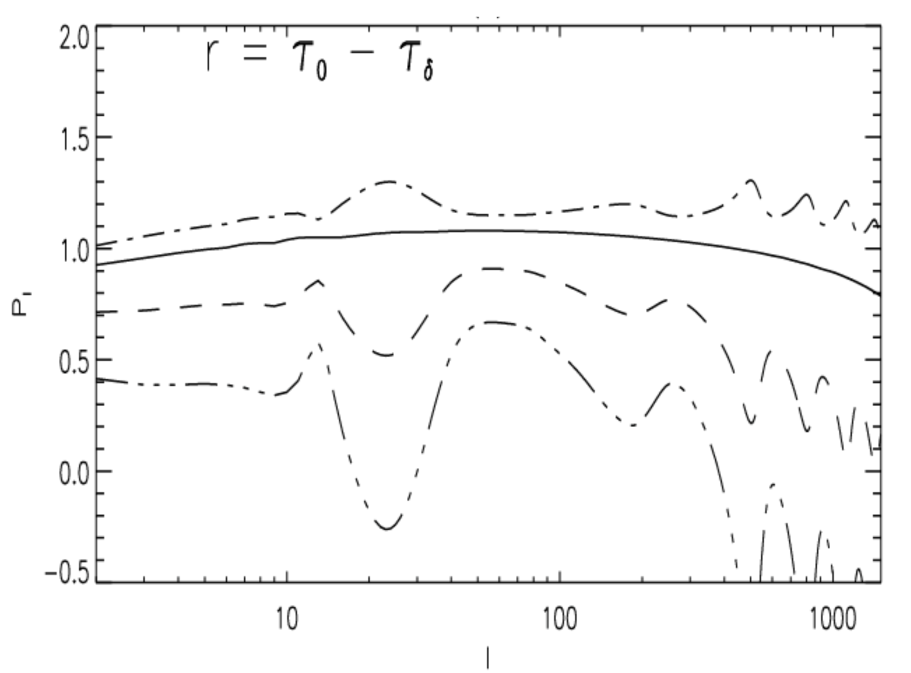


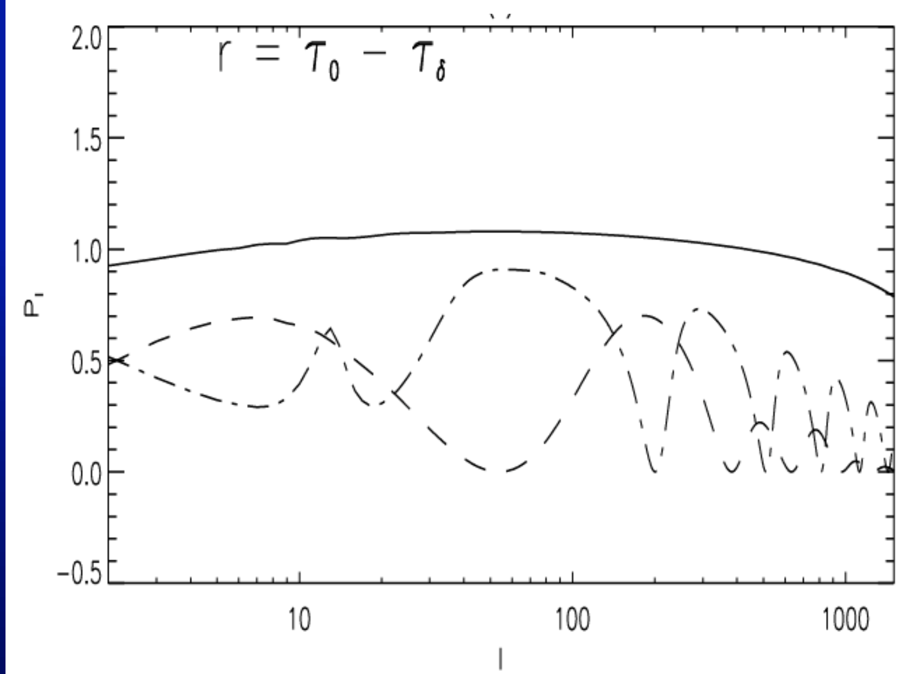
$$a_{lm} = F_l \int r^2 dr \left[\Phi_{lm}(r)\alpha_l^{adi}(r) + S_{lm}(r)\alpha_l^{iso}(r) \right] + n_{lm}$$

Komatsu, Spergel, Wandelt (2003); Yadav and Wandelt, PRD (2005), astro-ph/0505386

Reconstructing the primordial potential fluctuations using temperature and polarization

with reionization





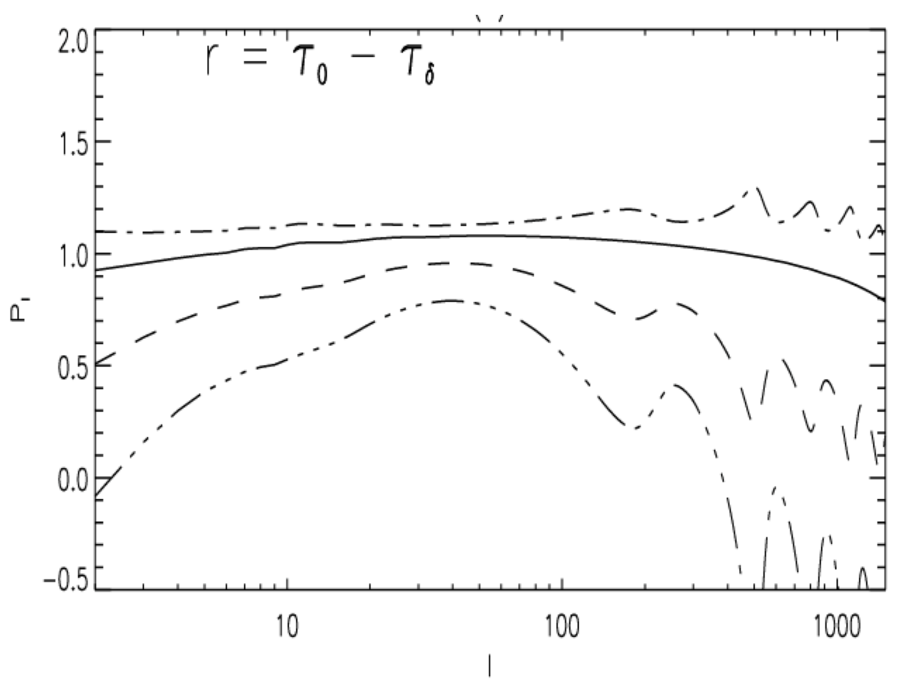
T and E combined

T and E separate

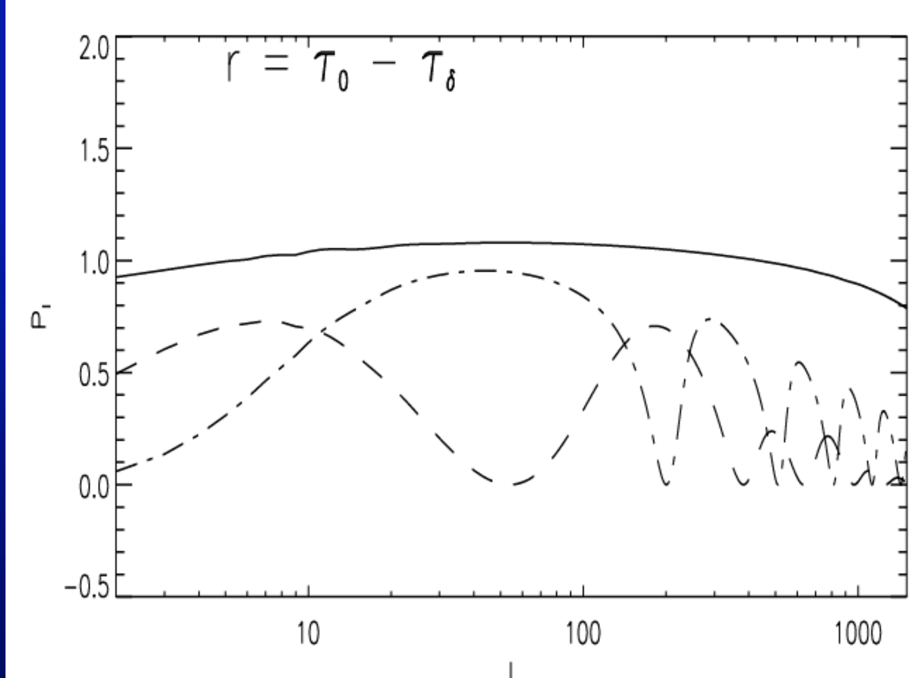
A. Yadav & B. Wandelt, astro-ph/0505386

Reconstructing the primordial potential fluctuations using temperature and polarization

no reionization

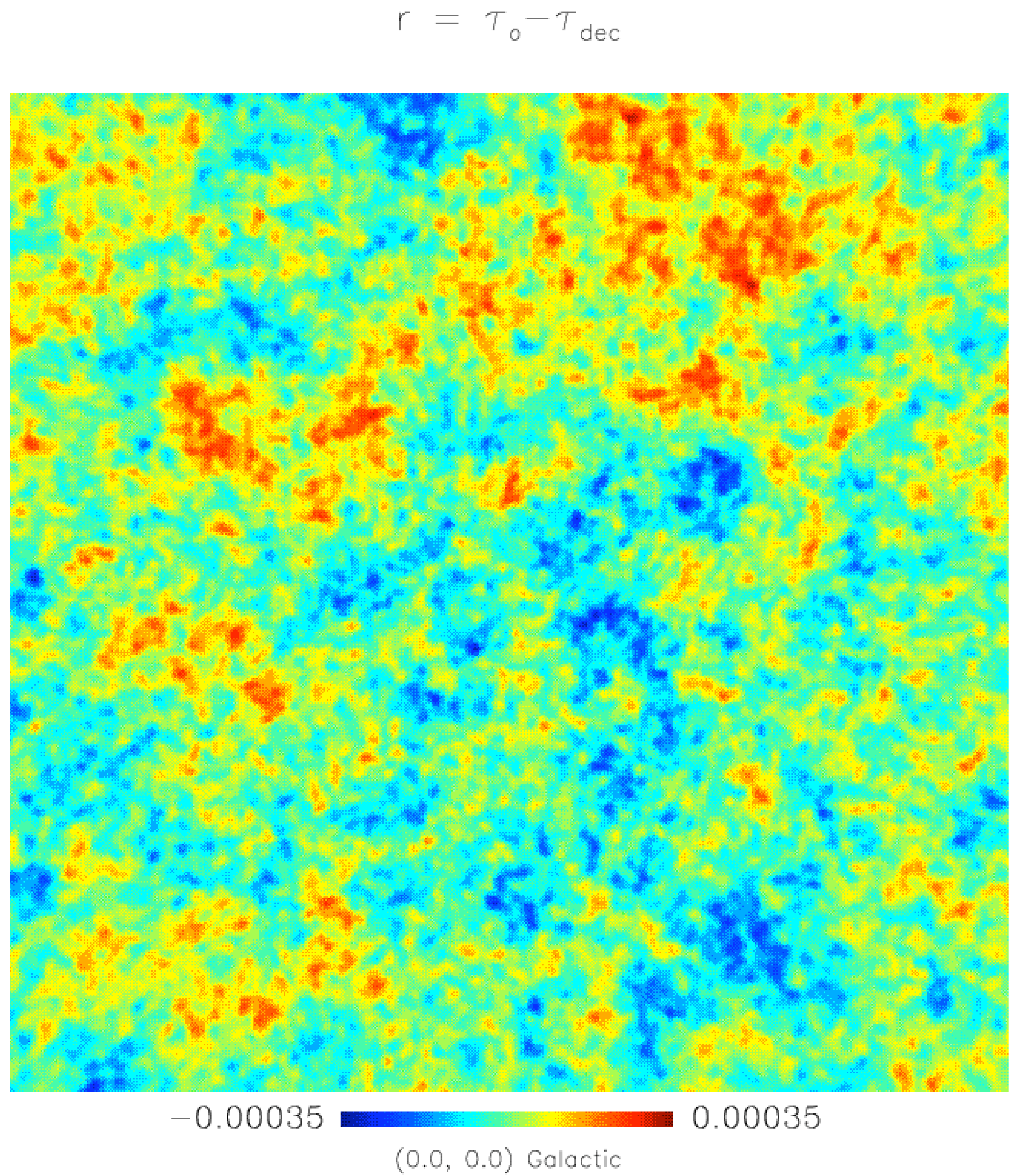


T and E combined



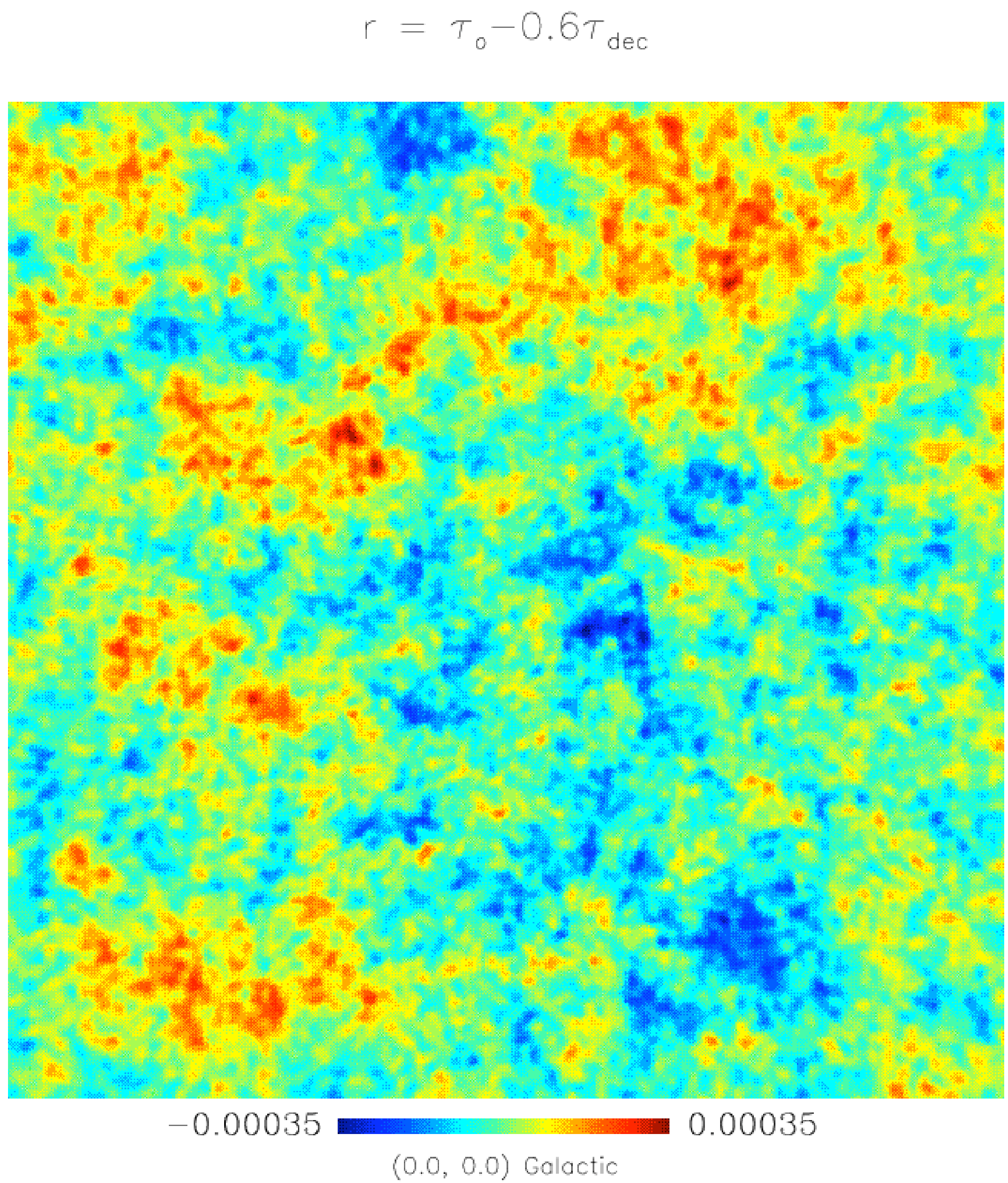
T and E separate

A. Yadav & B. Wandelt, astro-ph/0505386



Reconstruction of the primordial potential fluctuations from CMB temperature and polarization maps

A. Yadav & B. Wandelt, astro-ph/0505386



Reconstruction of the primordial potential fluctuations from CMB temperature and polarization maps

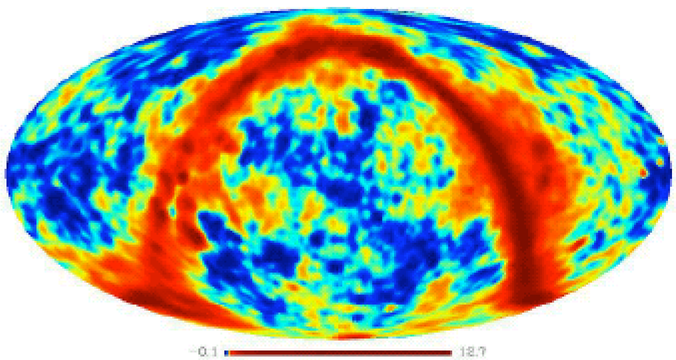
A. Yadav & B. Wandelt, astro-ph/0505386

The Next Generation

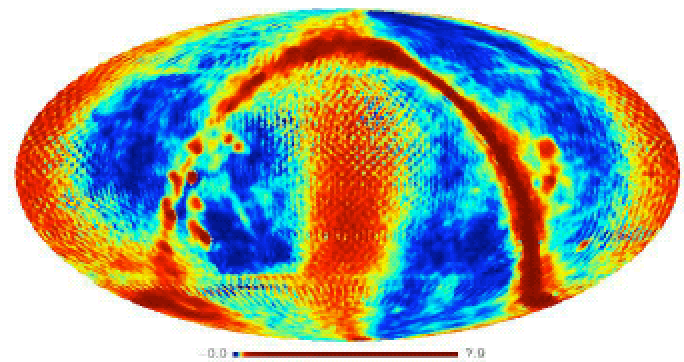
- New analysis techniques to enable next generation CMB missions (polarization B-modes)
- Example:
  - Deconvolution techniques to reject foregrounds and cross-polarization artefacts

Deconvolution removes foreground spill-over

True sky with Galaxy

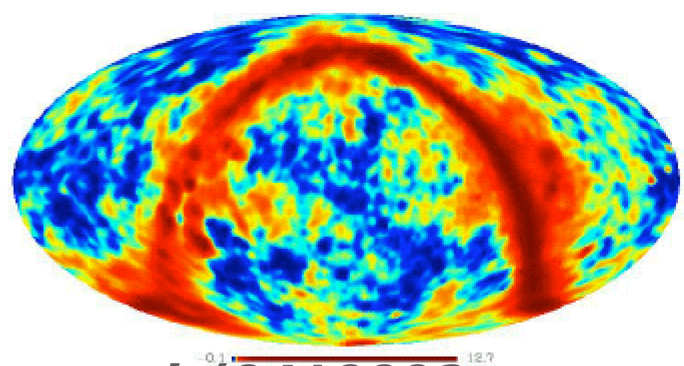


Standard map



- First-year WMAP Ka-band temperature map
- WMAP- like scanning strategy
- Sidelobe beam

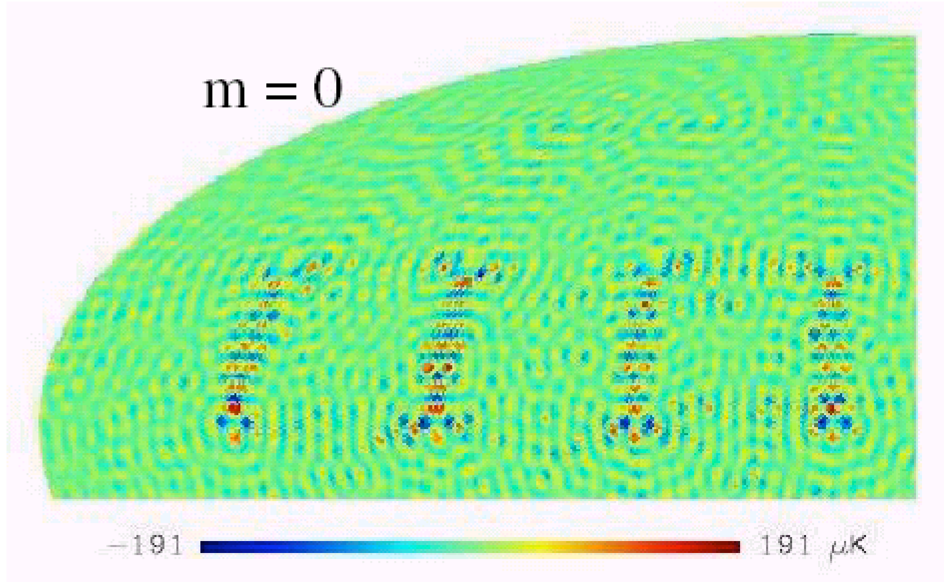
Deconvolution method

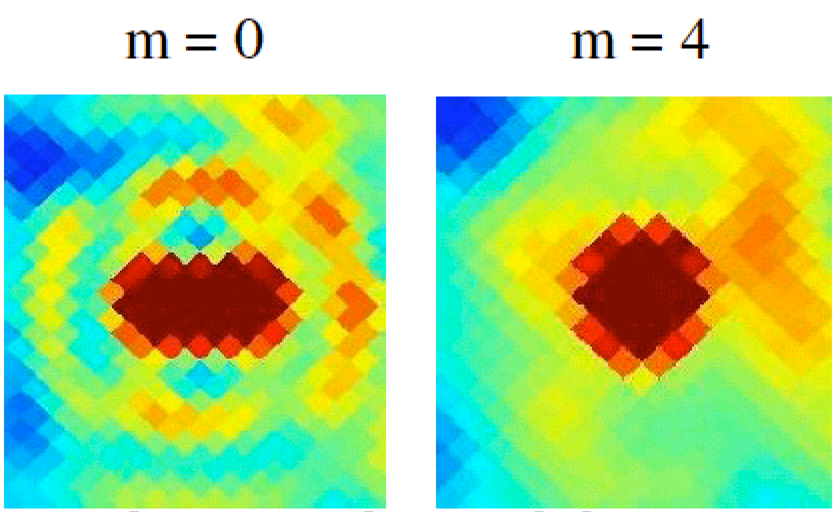


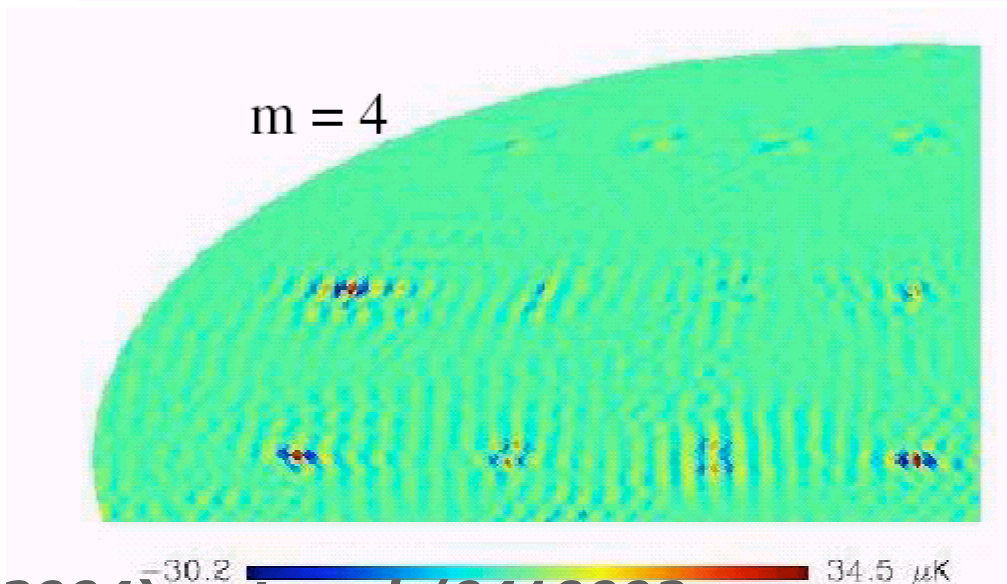
Armitage and Wandelt, PRD (2004), astro-ph/0410092

Beam Deconvolution removes artefacts

- originally convolved with elliptical beam
- m = 0 – assumes azimuthally symmetric
- m = 4 – mildly elliptical beam
- m = 38 – full description of original elliptical beam





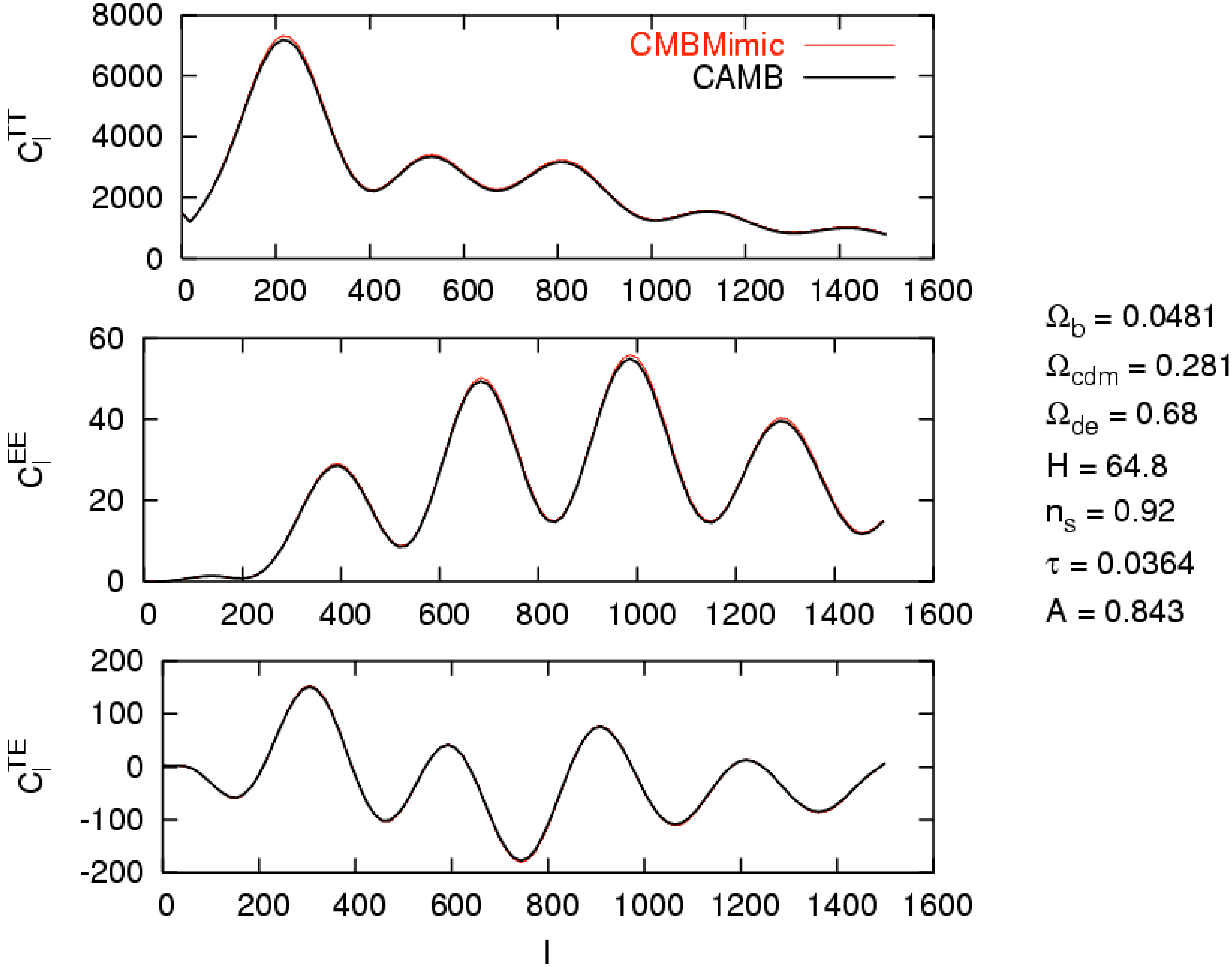


Armitage and Wandelt, PRD70 (2004), astro-ph/0410092

Joint parameter estimation in the future (10-15 parameters)

- Even MCMC Parameter estimation scales poorly with number of parameters
- Can the parameter estimation be sped up?
  - Better Monte Carlo techniques
  - Faster Boltzmann codes

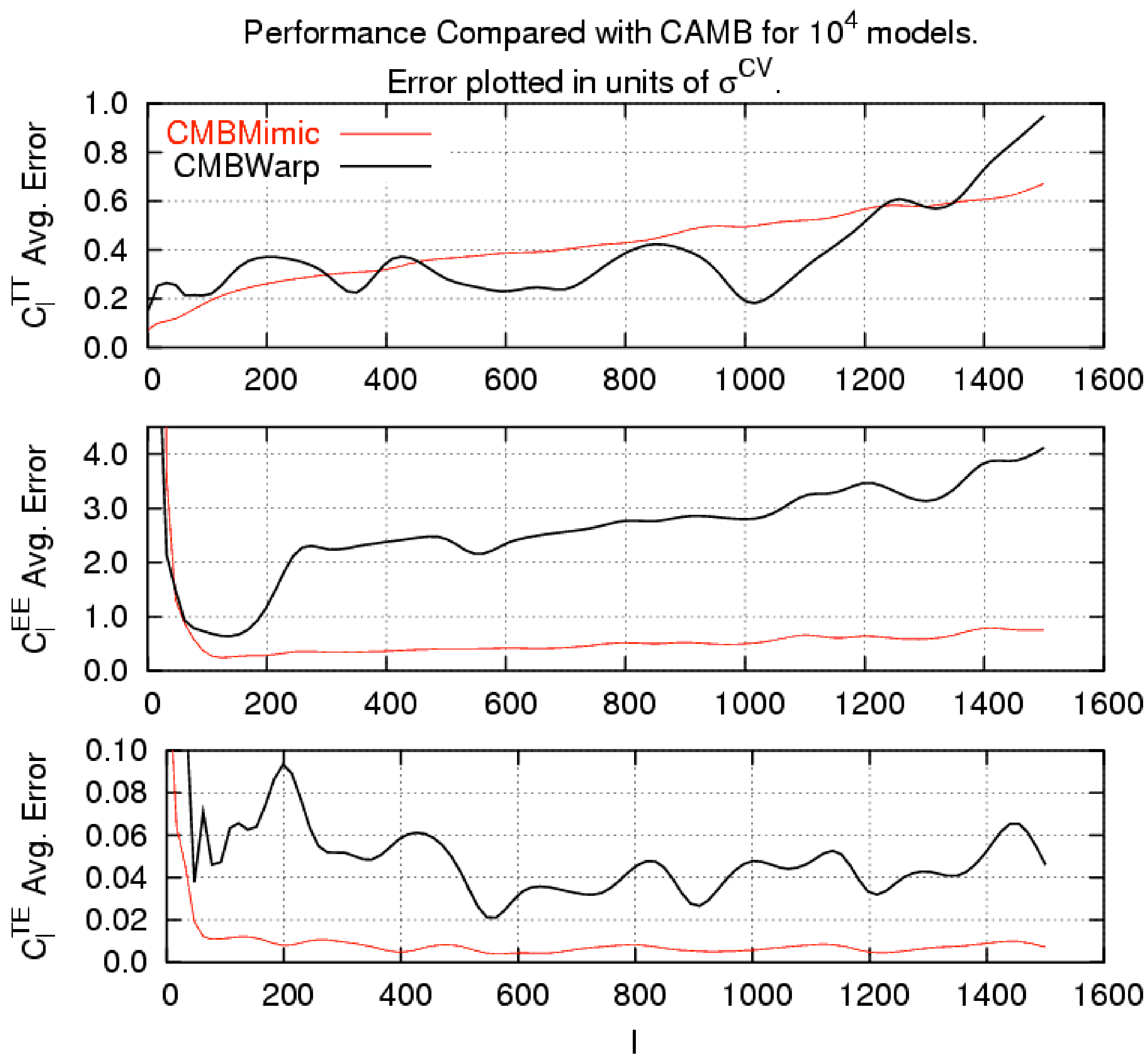
Accurate and fast cloning of Boltzmann Codes



Speed-up: 60-300

We use machine learning algorithms to mimic the action of B.Codes

Accurate to better than cosmic variance



Robust: *works over a broad region of parameter space*

Fendt and Wandelt, in prep.

Conclusions

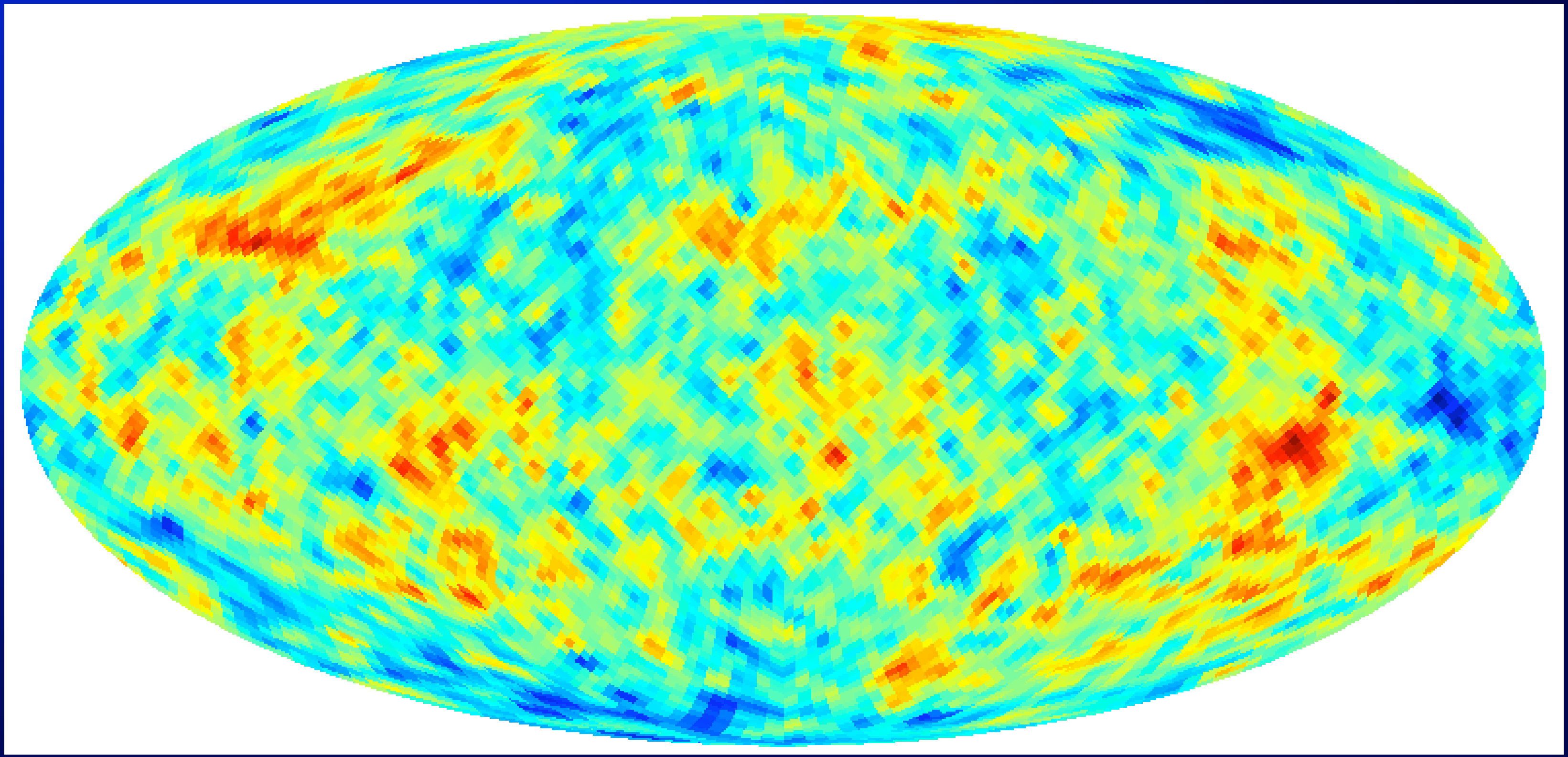
- The cosmic microwave background is a unique way to probe the concordance model
- Bayesian analysis using Gibbs sampling (MAGIC) is a fast and statistically exact way to go from data to cosmology with a very sophisticated model of the observations, including foregrounds and the combined analysis with other cosmological probes.
- Using this and other new techniques we can
  - deconvolve systematic effects;
  - probe for anomalies directly in the primordial scalar perturbations, combining both temperature and polarization observations;
  - explore large cosmological parameter spaces

The End

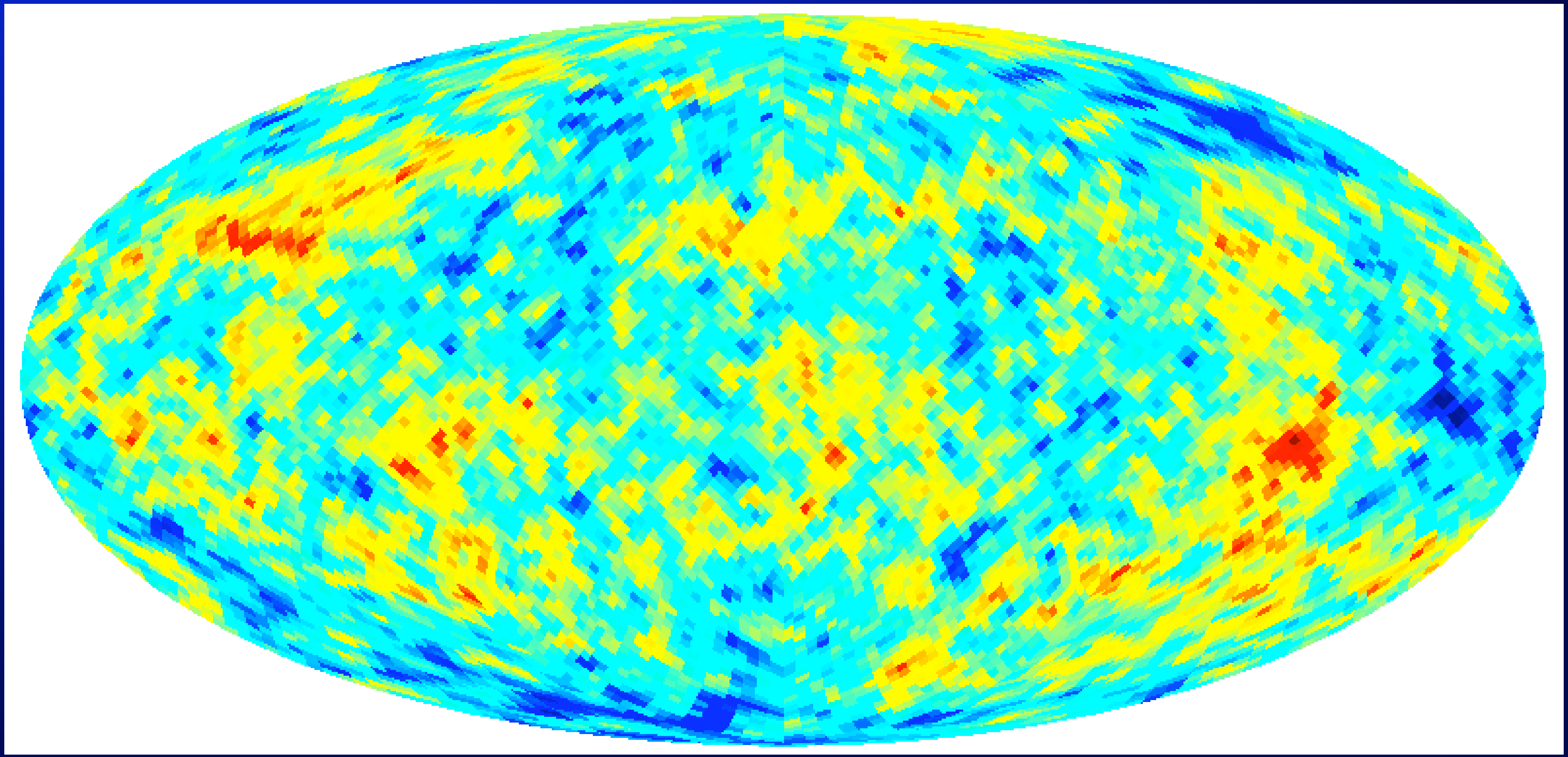
Example

Power spectrum estimation, filtering and reconstruction from noisy, censored data

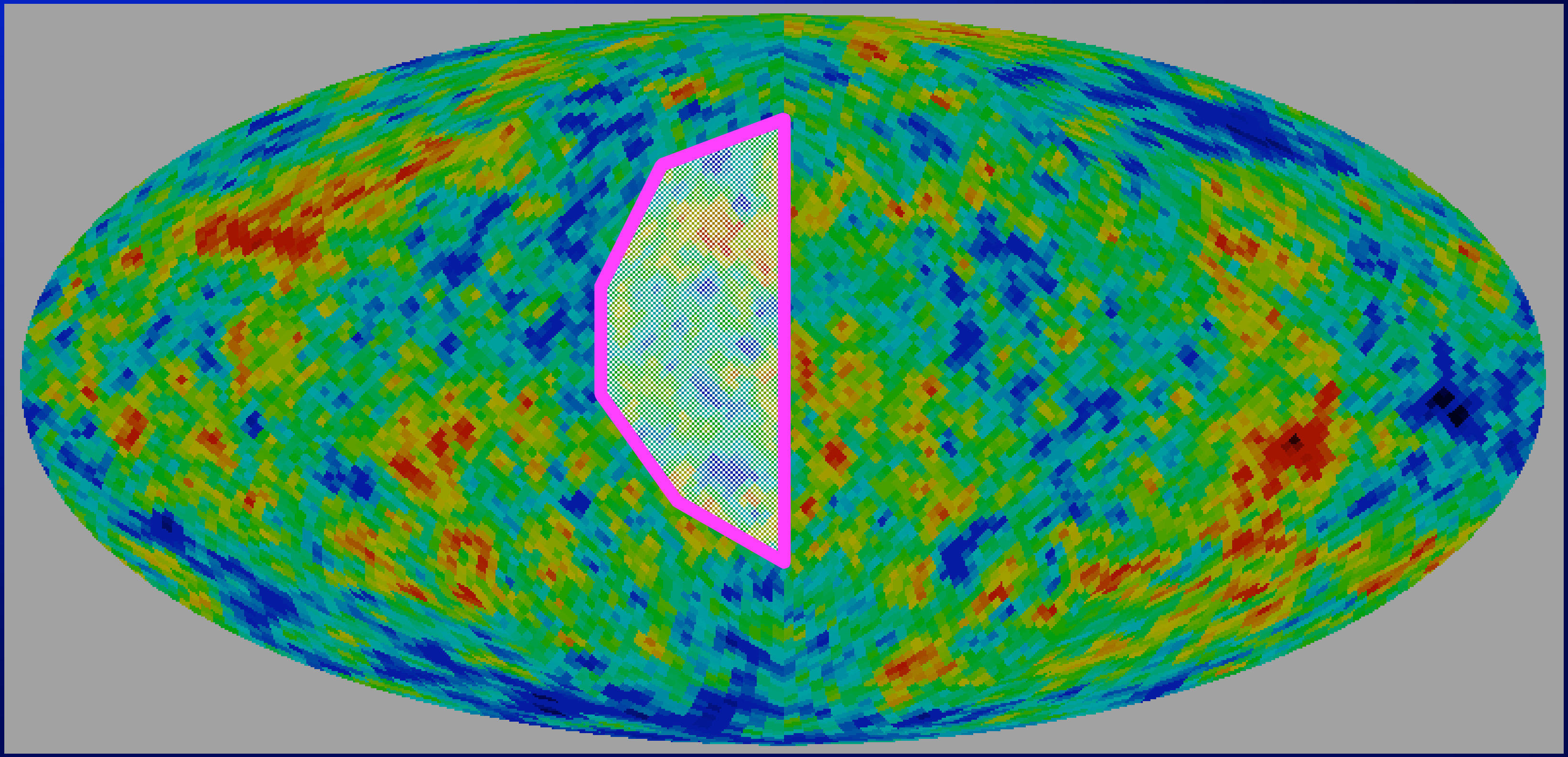
Simulated Signal



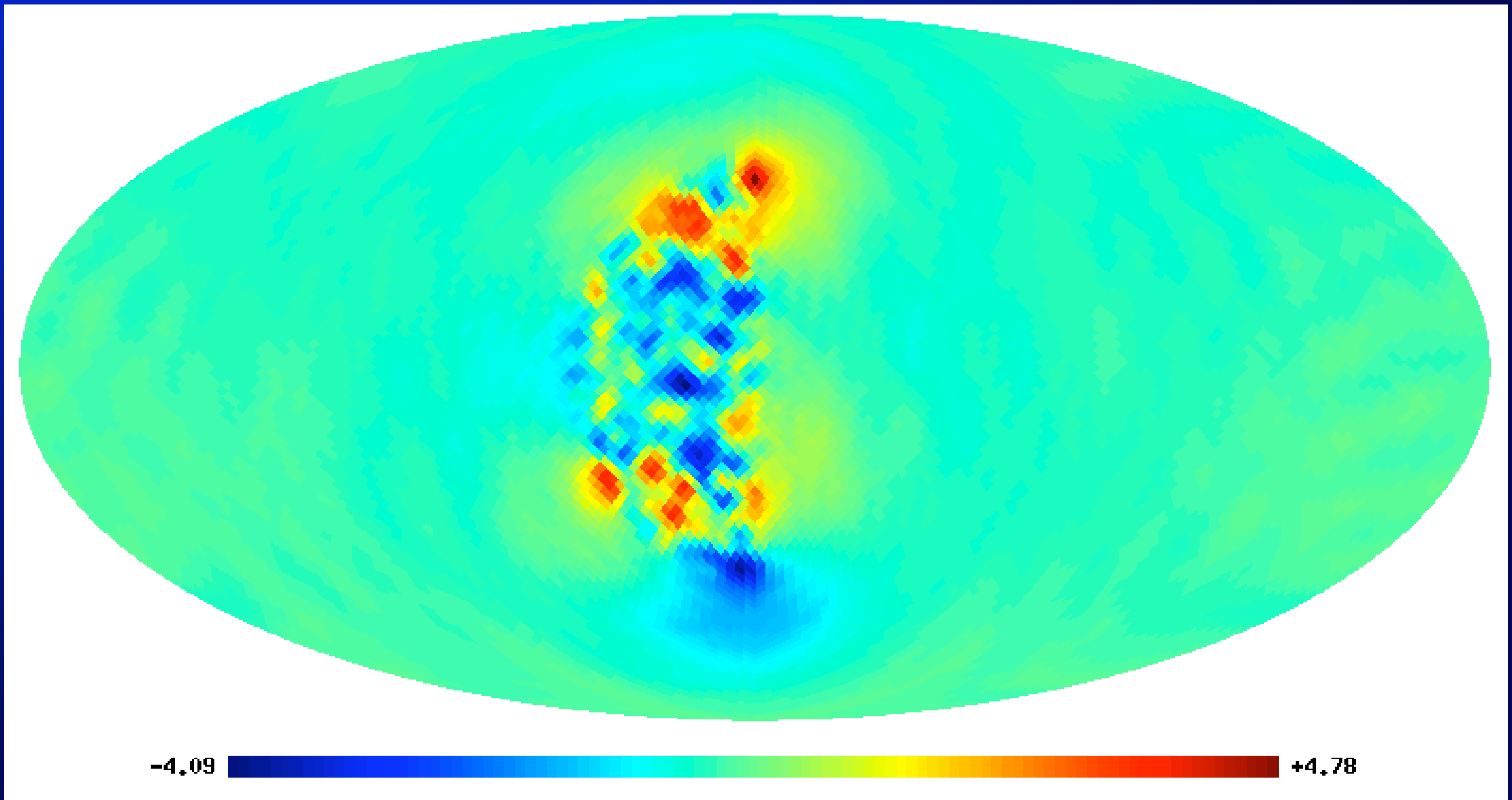
Simulated Signal + Noise



Censored

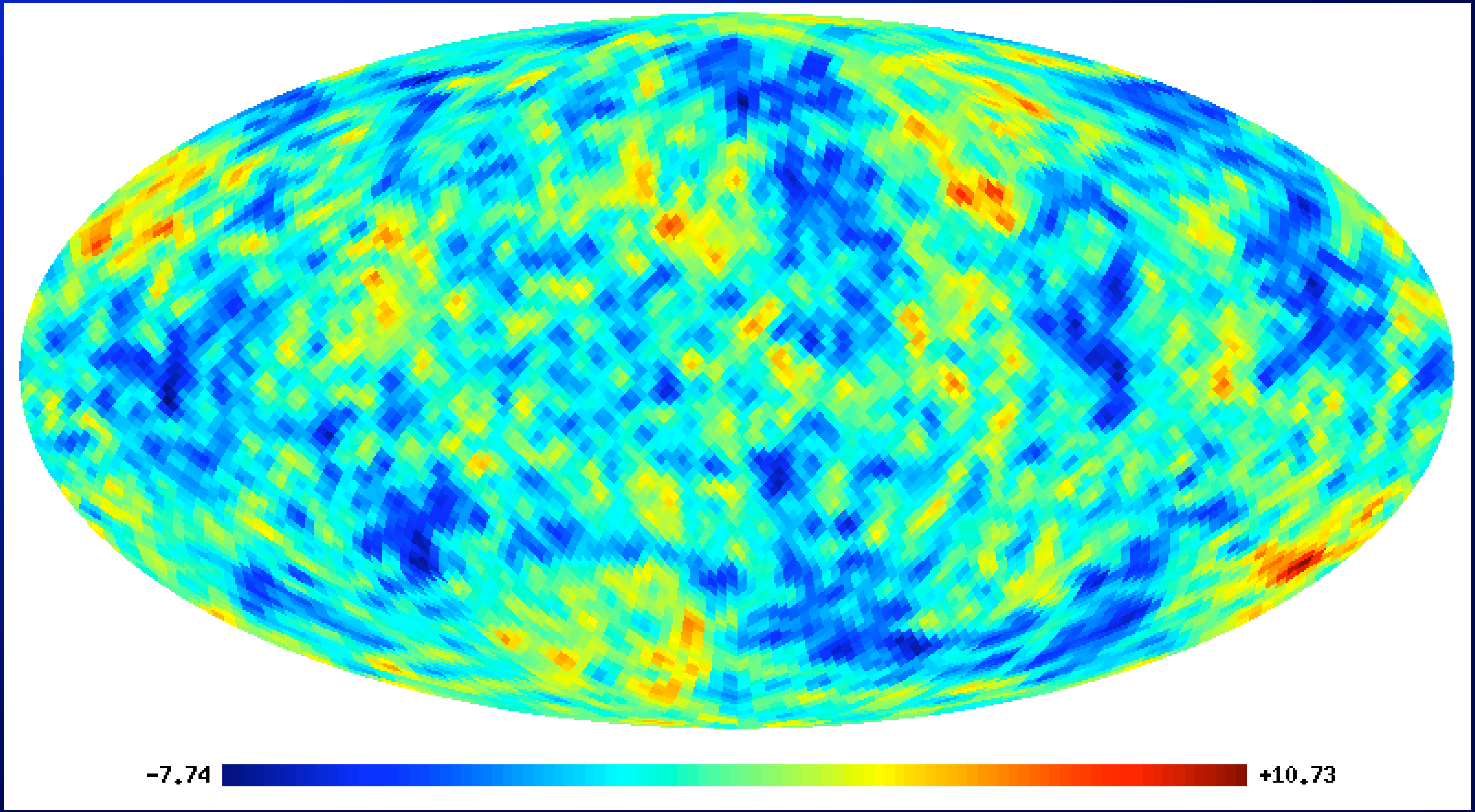


Simultaneous power spectrum estimation and Wiener filtering



A movie of samples of Wiener filtered signal supported by the data.

… and reconstruct pure signal CMB maps



movie of samples of pure signal skies consistent with the da